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landscape architect and educator, whose geospatially informed ecological planning and “sponge city” work expanded the horizon of resilient landscape practice

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Journal of Digital Landscape Architecture

11-2026

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Journal of Digital Landscape Architecture, 11-2026

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Statement of Purpose
The Journal of Digital Landscape Architecture addresses all aspects of digital technologies, applications, information, and knowledge pertaining to landscape architecture research, education, practice, and related fields. The journal publishes original papers in English that address theoretical and practical issues, innovative developments, methods, applications, findings, and case studies that are drawn primarily from work presented at the annual international Digital Landscape Architecture conference. Its intent is to encourage the broad dissemination of these ideas, innovations, and practices. Proposals for guest editors, topics, and contributions for special issues are welcome. The Journal of Digital Landscape Architecture is listed in the international citation database Scopus. It is in the top 35% of all journals in the engineering / architecture category. JoDLA is listed in DOAJ (Directory of Open Access Journals).

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The image shows one of Ireland‘s most iconic landscapes, designed by nature – the Cliffs of Moher. They stretch for about 14 kilometres and rise between 120 and 214 meters above the Atlantic Ocean. Looking at the image for a while, it might appear AI-generated, but it is actually a real photograph. While AI will undoubtedly dominate visual imagery in the future, the original will never be surpassed in its beauty and grandeur (Photographer: Giuseppe Milo, Year: 2014, Title: Cliffs Of Moher, Liscannor, Ireland; this file is licensed under the Creative Commons Attribution 3.0 Unported license).

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Preface

It was April 2024 when my colleague Pia Fricker from Aalto University and I met in Dublin, on my UCD campus, to serve as members of a selection committee the following day. The position we were to fill was an assistant professorship in Digital Landscape Design. A few weeks earlier, already aware that Pia would be coming to Dublin as an external reviewer, I saw an invitation to an evening lecture at UCD, during which the prestigious Ulysses Medal, the highest honour conferred by University College Dublin, was to be awarded to a gentleman I admittedly didn't know at the time. The event's reservation system allowed me to specify a guest I would bring, and so I entered Pia's name. In a later conversation with Pia – and I mention this only in my own selfish defence – I learned that she, too, was unfamiliar with this person. Early in the evening, Pia arrived on campus, and we had a welcome pint of Guinness at the student bar. Then we went to the assembly hall, and in a somewhat stiff and impersonal atmosphere, the recipient's medal was placed around his neck. An orchestra played, and then the medallist gave a celebratory speech. He began by saying that when he speaks, he prefers to explain something concrete to his audience rather than rambling on about general topics. He then started a slideshow of old-fashioned, homemade, and not particularly appealing slides, on which he explained the foundations of what he was being awarded the medal for: the first and original research foundations of what we now commonly refer to as AI – Artificial Intelligence. The man on stage was Geoffrey Hinton. When he spoke at UCD in April 2024, he hadn't yet won the 2024 Nobel Prize in Physics, which he shared with John J. Hopfield, for their foundational work enabling machine learning with artificial neural networks, the technology behind modern AI. We didn't know it, but we were sitting before the godfather of AI, and he explained to us, in the simplest, clearest, and most understandable way, what he and his colleagues had been thinking when the word AI didn't even exist, and what, in his opinion, AI is today and what it could become in the future. The Godfather of AI now believes that AI could become a real problem for humanity. Because, as he said, the way AI systems think and act is similar to human thinking, because it was directly derived from human thought by him and his colleagues. I remember realizing during the lecture that I was witnessing something absolutely extraordinary and captivating. Only afterward did I fully grasp what I had experienced. I had experienced a moment that, in my view, was comparable to Albert Einstein explaining the theory of relativity to us in a personal lecture or so. It was mind-blowing, kind of unbeatable. It was cutting edge.

None of us are Nobel laureates, and our papers don't win us Pulitzer Prizes or anything like that, but we have chosen “Cutting Edge” as the theme for this year’s DLA conference at UCD Dublin because we believe that a specialized conference format like the DLA is the right place to listen to those who are at the forefront of research in our field. What we mean by “cutting edge” is not the redundant application and over-repetition of methods and approaches that currently seem to be *en vogue*, but rather genuine pioneering work, the practical application of which doesn’t even need to be known yet. After his lecture at UCD, Geoffrey Hinton was asked by an Indian-born postdoc what advice he would give to young academics. After more than a minute of silent reflection, Hinton replied, “My advice is that if you think you’ve found something that you consider really important, work on it for a very, very long time, even if the rest of the world keeps telling you it's not important.” Said by a man who today practically personifies the AI megatrend but for decades was ridiculed by numerous

colleagues for continuing to work on things like Large Language Models, which most people simply didn't understand or couldn't understand.

Our goal in Dublin is to identify those topics that could become important in the future, in our field, and to identify the players who are truly cutting-edge. For this reason, we've decided not to maximize the number of presentations this time but rather to be selective when it comes to choosing which papers and content will be presented and discussed at DLA. There will be no parallel sessions so that all conference participants can attend all presentations and discussions together. This isn't about elitism; it's about enabling DLA attendees to fully participate in and contribute to what will advance our community – over two full intensive days. There's always the inherent risk of becoming stuck in a highly specialized scientific or professional community. In German, this is described as "stewing in one's own juices." Which is precisely what we want to avoid. We're hoping for intellectual sparring and heated discussions at DLA 2026 – even hall battles. We want to be genuinely challenged. We would be delighted if we all left exhausted but happy. And then we'll go to the pub. An Irish pub, of course.

Dublin, January 15, 2026

Assoc. Prof. Dr. Jörg Rekittke
School of Architecture, Planning and Environmental Policy, College of Engineering and Architecture, University College Dublin (UCD)

Introduction

We are pleased to present to you the eleventh issue of the Journal of Digital Landscape Architecture JoDLA 11-2026, with a total of 99 articles as result of the review process and one invited contribution. Three hundred and twenty authors from twenty-five countries sent in 145 extended abstracts in the initial phase. Thanks to the JoDLA review committee with eighty colleagues from twenty countries, we could select the final papers after two double-blind review phases. The contributions cover many current topics of digital landscape architecture. They came from a great number of Asian and American programs, from all German speaking programs, and from other programs across the globe. Research units, and vendors specializing in applications for landscape architecture and leading landscape architecture offices also contributed. The countries with the highest amount of entries are China, the Unites States and Turkey. We are very happy that publishing in the Journal of Digital Landscape Architecture JoDLA has become an unwritten expectation – practically a requirement – for recognition/success in some university departments, and we will do our best to keep and develop this standard.

After being listed in Scopus, the journal is now also listed in DOAJ (Directory of Open Access Journals). Wichmann publisher has been making the JoDLA, and its forerunner publication Digital Landscape Architecture, accessible as open access papers since 2013, and therefore provides more than ten years' documentation of research in the area of Digital Landscape Architecture.

The cover of this issue shows one of Ireland's most iconic landscapes, designed by nature – the Cliffs of Moher at Liscannor, Ireland. They stretch for about 14 kilometres and rise between 120 and 214 meters above the Atlantic Ocean. The image was taken by the photographer: Giuseppe Milo and selected by Prof. Dr. Jörg Rekittke, the local DLA Chair in Dublin, the location of this year's Digital Landscape Architecture Conference at University College Dublin UCD. The DLA 2026 is being organized by the experienced team of Prof. Dr. Jörg Rekittke and supported by Dr. Stephen Ervin who organized the DLA twice in Boston.

Looking at the image for a while, it might appear AI-generated, but it is actually a real photograph. While AI will undoubtedly dominate visual imagery in the future, the original will never be surpassed in its beauty and grandeur.

This image is a great icon for the DLA 2026 focusing on **"Cutting Edge"**. But – being analog – it is also a great starting point on the challenges of AI in landscape architecture.

In addition to the main theme, we provided a number of other possible areas for submitting papers on current research or outstanding practice in digital landscape architecture. We can now present the result of a rigid two-phase double-blind review process.

This eleventh issue of the Journal of Digital Landscape Architecture, 11-2026, covers 100 contributions, each on one of the following twelve current areas of research and prototype applications in digital landscape architecture:

- AI, Machine Learning and Generative Design Tools
- AI Ethics, Frameworks and Data Analysis
- 3D Scanning, Point Clouds and BIM Modeling

- VR, AR and Immersive Visualization Technologies
- Digital Tools, Data Systems and Software
- Urban Heat, Thermal Comfort and Microclimate
- Water Management, Hydrology and Coastal Resilience
- Ecosystem Services, Biodiversity and Ecological Networks
- Geospatial Analysis, Urban Ecology and Planning
- Environmental Monitoring, Remote Sensing and Data Collection
- Participatory Design, Community Engagement and User Experience
- Landscape Architecture Education, Pedagogy and Curriculum

We hope you will appreciate the eleventh edition. Printed copies will be available at the conference- Note hardcopies sent out on request to authors. You may also order copies by the publisher.

You will find all the contributions online as open access publications at the gis.Point and gis.Open platforms of Wichmann http://gispoint.de/jodla.html.

We would also like to invite you to the next DLA conference. The 28th international conference on information technology in landscape architecture, Digital Landscape Architecture DLA 2027 with the main theme “From Planning to Transformation: Digital Pathways in Landscape Architecture” will be held at Anhalt University in Dessau, Germany from June 2-4, 2027.

Furthermore, we can already announce that the DLA 2028 will be hosted by at Utah State University.

The Journal of Digital Landscape Architecture invites you to submit ideas for special issues and topics. Please follow our continuously updated announcements and call for papers and posters at www.dla-conference.com. Here you will also find the complete online documentation of the DLA beginning in 2013. For earlier contributions to DLA publications, you may ask our JoDLA office.

We thank all those who have been supporting the DLA conference all these years and who are helping develop the journal now for the eleventh year. Please keep your critical eye upon us and help grow the number of DLA contributions.

Erich Buhmann, Pia Fricker, Stephen Ervin, James Palmer and Jörg Rekittke

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AI, Machine Learning and Generative Design Tools

Radiance Fields and Spatial Artificial Intelligence: Synthetic Landscape Modeling with SHARP

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Abstract: Spatial artificial intelligence is driving a quiet revolution in inference-based landscape modeling. In landscape architecture, established forms of digital representations, based on discrete data structures and geometries, favor stable surfaces and bounded objects at the expense of the atmospheric, temporal, and porous qualities through which landscapes are encountered. Radiance fields, including representations structured through 3D Gaussian splatting (3DGS) and Neural Radiance Fields (NeRF), encode landscapes as continuous volumetric fields of light, generating navigable 3D environments from image-based observations.

This paper positions radiance fields as a distinct and emerging category of landscape representations and examines their relevance for landscape architecture through SHARP (Single-image High-Accuracy Real-time Parallax), a novel model by Apple that synthesizes metric-scale 3D Gaussian radiance fields from a single image, preserving absolute spatial dimensions relevant to bodily experience and design reasoning. Trained on large-scale synthetic and real-world data, SHARP infers spatial structure, scale, and visibility from minimal input, collapsing fragmented sensing and modeling processes into a unified inference framework.

Infrared imagery captured in Dublin (Ireland), including at the National Botanic Gardens and Killiney Hill Park, serves as input to generate a series of 3D Gaussian reconstructions. In this context, SHARP enables high-fidelity, near-instantaneous synthetic landscape modeling, providing an accessible framework for design research and education. In addition to our model explorations, the approach is further validated through pedagogical experiments with students in a landscape architecture studio at UCD Dublin.

The paper frames radiance fields as an emerging form of spatial artificial intelligence and employs SHARP to substantiate a shift from technically fragmented and epistemically stratified processes toward quasi-intuitive, inference-based engagements with landscapes. Rather than definitive spatial records, radiance fields serve as probabilistic spatial propositions whose validity lies in coherence and situated inference rather than exhaustive measurement and uniform sampling, reframing landscapes as fields of conditions shaped by an internalized set of relationships. Recognizing radiance fields as an operative paradigm for sensing and modeling landscapes clarifies their role as a distinct representational framework for landscape architecture.

Keywords: Radiance fields, Gaussian splatting, SHARP, spatial artificial intelligence, inference-based modeling

1 Radiance Fields: Categorization, Implementations, and Relevance for Landscape Architecture

Radiance fields model the distribution of light within a target scene. Instead of defining a scene through geometric features or surfaces, radiance fields prioritize the propagation of light as the primary target of modeling, shifting emphasis from spatial form toward spatial quantities of light. Radiance fields interpolate between the light conditions captured in image-based observations to estimate how the scene would be perceived from arbitrary viewpoints

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in 3D space. This enables novel view synthesis, allowing the generation of views not initially captured by the training data. Radiance field models serve as navigable environments – continuous volumetric fields of light – that respond dynamically to user interactions, adapting conditions such as radiance, reflections, and translucency for each viewpoint.

The unique characteristics of radiance fields, combined with advances in processing and rendering efficiencies, have led to the proliferation of a diverse array of related yet distinct models. Specialized implementations optimize radiance field models for specific metrics, such as processing and rendering efficiency, representational accuracy, visual quality, and extent or complexity of the scene. The terminology and category of radiance fields relate to what is being modeled – the distribution of light within a scene – while accommodating multiple approaches to structuring and representation.

Fig. 1: SHARP-generated radiance field from within the Palm House at the National Botanic Gardens (Site 1), with the foreground fading into darkness and the background illuminated, emphasizing depth, enclosure, and the volumetric light conditions

1.1 Implicit and Explicit Representations

Radiance fields encode light distribution through two distinct and structurally opposed approaches: implicit and explicit representations.

Implicit representations, such as neural radiance fields (NeRF), compute and store light distribution as a continuous function encoded by a neural network. The neural network is queried for every set of position and viewing direction to generate new views – the neural network is the model. Beyond their spatial extent and sampling density, these models conventionally do not encode explicit geometries or formalized spatial data structures. Building on the foundations laid by MILDENHALL et al. (2020), the development of Instant-NGP (MÜLLER et al. 2022) achieved significant performance improvements in training and rendering radi-

ance fields, effectively reducing computational overhead and enabling a broader range of users to engage with radiance fields. The advancements of the approach by Müller et al. (2022) surpassed a pivotal technical threshold, allowing speculation on the uses of neural radiance fields for landscape architecture (SCHOB & REKITTKE 2023).

Explicit representations operate through a finite collection of spatial samples of the function, such as 3D Gaussians (KERBL et al. 2023). These representations employ discrete primitives, which are projected onto the image plane for rendering. Each Gaussian stores a set of attributes, including position, scale, orientation, opacity, and radiance encoded as color (KERBL et al. 2023). While a neural optimization may be used for training, a neural network is generally not required for inference (rendering). While explicit representations are structurally simpler than their implicit counterparts, their reduced hardware requirements and enhanced rendering speeds facilitate a more immediate interaction with the spatial environments they encode. Since its introduction in 2023, the increased accessibility of 3D Gaussian splatting has catalyzed its broad adoption, enabling users to integrate explicit radiance fields into standard design and visualization workflows.

1.2 Implementations and Previous Research

Developed in the field of computer vision for tasks such as digital reconstruction, visualization, simulation, and animation, radiance fields are increasingly transitioning from experimental implementations toward seamless integration into established platforms. This includes standalone applications for explicit representations, such as LichtFeld Studio (LICHTFELD STUDIO 2026), Postshot (JAWSET VISUAL COMPUTING 2025), KIRI Engine (KIRI INNOVATIONS 2026b), Polycam (POLYCAM INC. 2026), or the web-based SuperSplat Editor (PLAYCANVAS LTD., 2026); and implicit representations such as Nerfstudio (TANCIK et al. 2023), and Instant-NGP 2.0 (MÜLLER et al. 2025). ESRI's integration of Gaussian splatting into their ArcGIS product family facilitates georeferencing and geospatial analysis for splat-based models (NORTH et al. 2025), emphasizing their enhanced visual quality, particularly the realistic visualization of vegetation and more accurate representation of materials (SELER 2025). Beyond these integrations, radiance fields for novel view synthesis with NeRF and Gaussian splatting are increasingly included in benchmark datasets, for example, to create digital twins (WYSOCKI et al. 2025). In addition, radiance fields are used for applications in architectural heritage (JAMIL & BRENNAN 2025), historic garden reconstruction (Li et al. 2025), and urban architectural virtual realities (PEZZICA et al. 2024).

Radiance fields provide an expanded contextual framework for the sensing, modeling, and visualization of landscapes in landscape architecture (SCHOB & REKITTKE 2023). Radiance fields shift representation from discrete spatial structures toward continuous fields of conditions. This positions them as a distinct representational paradigm in landscape architecture, complementary to conventional models and technical drawings, as well as photogrammetry- and lidar-based approaches, while emphasizing spatial context, atmospheric conditions, and situated spatial encounters (SCHOB & REKITTKE 2023). The project Fields of Light (SCHOB 2025), presented at the 7th Lisbon Architecture Triennale (2025), extends this conception by foregrounding light as a primary landscape condition, using infrared Gaussian splatting models to articulate how radiative fluxes, atmospheric scattering, and material translucency condition forest landscapes around Oslo in Norway. Currently, we are testing applications for radiance fields in landscape architecture in a Landscape Design Studio at the University Col-

lege Dublin (UCD), School of Architecture, Planning and Environmental Policy (REKITTKE 2026). Building upon this work, this paper investigates radiance fields as a distinct category of landscape models, emphasizing their capacity to capture continuous, atmospheric, and situated landscape conditions.

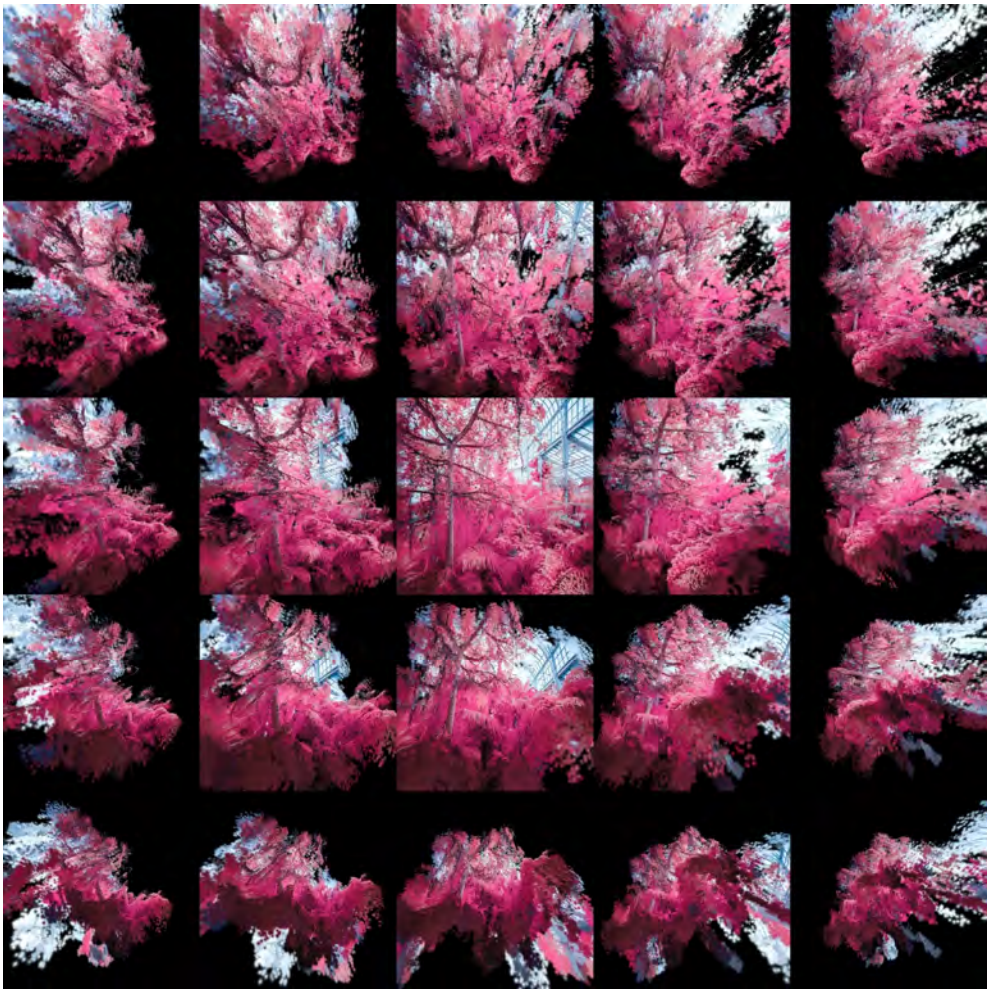

Fig. 2: SHARP-generated radiance field from within the Palm House at the National Botanic Gardens (Site 1), illustrating how the inferred radiance field is rendered from multiple nearby viewpoints relative to the original camera position (center)

1.3 Implications for Landscape Architecture

Beyond their technical characteristics, an engagement with radiance fields holds significant conceptual implications for landscape architecture, including the production of continuous landscape models with visual coherence beyond their underlying data structures, the integration of dynamic target conditions, the capacity to model conditions disregarded by previous approaches, and concrete alignments with remote sensing processes.

Radiance fields encode their target systems as continuous fields rather than discrete entities, which more closely aligns with conceptions of landscapes in landscape architecture (SCHOB & REKITTKE 2023). Rather than being confined to surfaces or discrete objects, radiance fields operate as multi-resolution volumetric fields and are therefore less constrained by the limitations of previous point- or vector-based methods. Their multi-resolution structure enables inference of an expansive landscape context without a proportional increase in data density, concentrating computational resources on perceptual and spatial salience rather than on uniform sampling. For example, reflecting on inefficiencies of lidar data, GIROT (2019) observes that "ninety-nine per cent of the scanned data is seldom used and usually discarded" (GIROT 2019, 113).

The introduction of radiance field models reframes the progress achieved by established sensing technologies. While point-based methods such as lidar scanning may provide superior spatial precision, the capacity to generate dense volumetric models from image-based observation, including historical non-technical photographs, challenges the interdependence of visual and spatial dimensions in sensing and modeling. This includes an asymmetry in data conversion: while point clouds or meshes may be derived from radiance fields, the inverse process is significantly more complex, if not entirely impossible.

Radiance fields appear to change dynamically as the observer moves through the scene, continuously adapting brightness, color, and opacity based on the observer's position and viewing direction. This experiential correspondence more closely aligns with human visual cognition. Additional target conditions, such as a temporal component, can further enhance the model's capacity to accurately capture target conditions or facilitate the simulation of changes within them. 4D Gaussian splatting (WU et al. 2024), for example, encodes three spatial dimensions and time (x, y, z, t) for each Gaussian. Even input data captured at different moments in time can be integrated into a single, multi-temporal radiance field that contains different states of the target system (SCHOB & REKITTKE 2023).

Radiance fields capture target conditions that may be registered as noise by other sensors or remain entirely excluded from conventional data structures (SCHOB & REKITTKE 2023). This includes target properties such as "absorptivity, reflectivity, scattering, challenging texture, and complex shape or geometry" (SCHOB & REKITTKE, 2023, 437), conventionally encountered in water-surface reflections and turbidity, light scattered through clouds or fog, and the diffusion of light by vegetation. In landscape architecture, this expands the scope of what can be sensed and modeled, foregrounding ephemeral conditions that structure landscapes yet are excluded from conventional spatial representations.

Although radiance fields are primarily associated with image-based modeling in computer vision and 3D reconstruction rather than with remote sensing processes, their characterization of the distribution of light within a scene directly relates to conditions such as radiative transfer processes and signal registration in remote sensing. A radiance field model, therefore, can

retroactively enhance the characterization of the conditions within the target scene, beyond the limitations of the sparse data structures that serve as model input. In this manner, sensing and modeling operate as recursive and intertwined processes (SCHOB 2026).

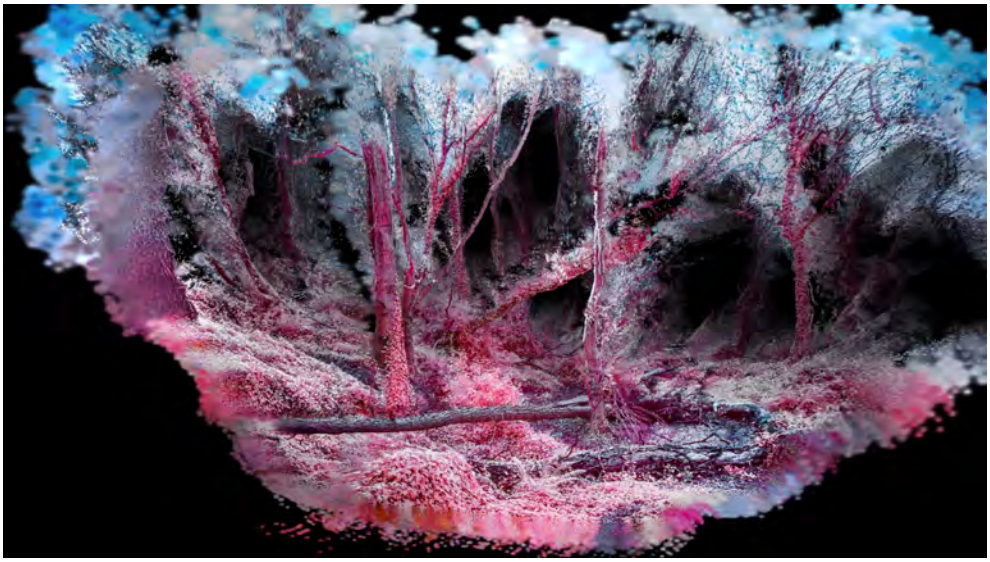

Fig. 3: SHARP-generated radiance field of a forest scene at Killiney Hill Park (Site 2), showing the spatial extent of the inferred reconstruction and the increase in Gaussian splat size toward its outer regions

2 SHARP

SHARP (Single-image High-Accuracy Real-time Parallax) is a novel model for "real-time photorealistic rendering of nearby views from a single photograph" (MESCHEDER et al. 2025, 9). While other models are designed to generate radiance fields from multi-view training data, meaning a scene captured from multiple viewpoints, SHARP focuses on generating a radiance field from a single RGB image (MESCHEDER et al. 2025).

SHARP takes a single image as input and generates 3D Gaussian representations as output. The model "synthesizes a 3D Gaussian representation via a single forward pass through a neural network" (MESCHEDER et al. 2025, 9), which "can then be rendered in real time at high resolution from nearby views" (MESCHEDER et al. 2025, 9). Each Gaussian encodes a defined set of attributes, including position, scale, orientation, color, and opacity (MESCHEDER et al. 2025). View-dependent effects are encoded using a layered depth approach rather than continuous angular functions, such as spherical harmonics. This constitutes a deliberate shift from the complex modeling of directional light conditions toward the modeling of visibility and occlusion, prioritizing perceptual coherence and computational efficiency over more detailed representations. This approach is efficient in representing vegetation, porous structures, and (partially) transparent features.

SHARP was trained on the combination of synthetic and real-world data. The synthetic training data were "generated using an in-house procedural content generation system" (MESCHEDER et al. 2025, 15), which "supports random placement of various object types, including thin structures, transparent materials, and reflective surfaces, across a wide range of spatial configurations" (MESCHEDER et al. 2025, 15). The synthetic data consist of "artist-made environments, comprising over 2K outdoor and 5K indoor scenes" (MESCHEDER et al. 2025, 15), which are "rendered using the V-Ray physically based rendering engine, ensuring photorealistic lighting and material interactions" (MESCHEDER et al. 2025, 16). The real-world training data consists of data from "OpenScene (2023) as well as a collection of high-quality photographs from Shutterstock, Getty Images, and Flickr" (MESCHEDER et al. 2025, 16).

SHARP infers real-world dimensions from image pixel values – outputs are "metric, with absolute scale" (MESCHEDER et al. 2025, 1) – based on a multi-stage training process to establish precise relationships between 2D images and 3D space. While the synthetic data used in the first training stage provides precise dimensions, the real-world data employed in the second stage fine-tunes the model for natural light conditions and material properties. Unlike many other image-based reconstruction models, which merely determine relative depth and proportional spatial relations, SHARP generates representations that employ standard physical units (e. g., meters) and a consistent absolute scale, reflecting real-world dimensions within the scene. While this does not entail alignment with global coordinate reference systems (yet), it implies that the generated environments preserve the physical dimensions of features within their target systems, independent of the resolution or viewpoint of input images. SHARP's ground truth dimensions are based on synthetic images (GIL-FOURNIER & PARIKKA 2021).

Metric scaling establishes a direct relationship between human and landscape scales, thereby enabling meaningful siting of bodily movement, eye height, and spatial experience. In digital environments, consistent metric scaling enables the synchronization between physical and virtual movements for virtual and augmented reality (VR and AR) applications (MESCHEDER et al. 2025). Within landscape architecture, scale functions not merely as a representational convention but as an operative framework through which spatial relations, bodily engagement, and design intentions are negotiated across sites. In addition, consistent scaling enables the seamless combination of models derived from disparate images into unified scenes.

SHARP is computationally more efficient than comparable models, providing for "state-of-the-art image fidelity for nearby view synthesis" (MESCHEDER et al. 2025, 9) using conventional hardware, such as a laptop or smartphone. While MESCHEDER et al. (2025) explicitly mention the advantages of neural radiance fields (NeRF) and spherical harmonics, the use of a 3D Gaussian representation and a layered depth approach prioritizes training and rendering efficiency over visual fidelity. In this regard, the broad adoption of previous radiance field models, such as Instant-NGP (MÜLLER et al. 2022) and 3D Gaussian splatting (KERBL et al. 2023), was equally conditioned by their increased performance, emphasizing that efficiency improvements are not merely technical or computational optimizations, but a prerequisite for a transition into mainstream applications and use cases.

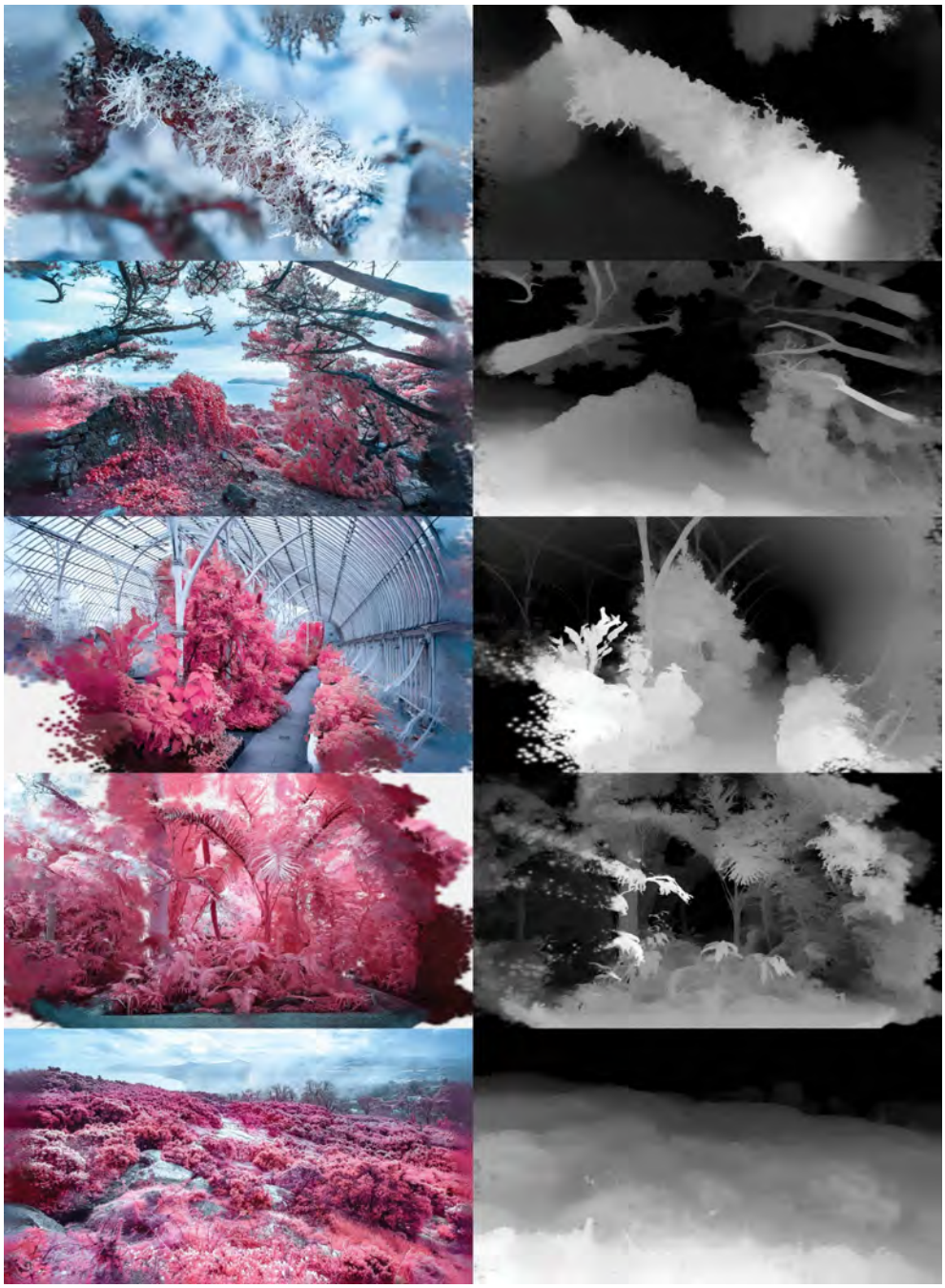

Fig. 4: SHARP-generated radiance fields (left) and corresponding greyscale depth maps (right) from the same viewpoints across Site 1 (rows 3, 4) and Site 2 (rows 1, 2, 5), illustrating the relation between perceptual coherence and inferred depth structure

3 Model Explorations with SHARP

We employ SHARP to generate volumetric 3D Gaussian radiance fields from single image inputs. To test and demonstrate the versatility of the model, rather than focusing on a single case or site, we employ a selection of images capturing varied target conditions, including differences in spatial extent, diverse landscape typologies, and varying light conditions. While other image-based reconstruction methods rely on structured capture protocols and constrained acquisition geometries, such as linear or orbital movements centered on a target, SHARP achieves high-quality reconstructions largely independent of the capture context, demonstrating "robust zero-shot generalization across datasets" (MESCHEDER et al. 2025).

The data for this case consist of infrared imagery captured with a converted full-spectrum camera in combination with a selection of infrared filters. Vegetation exhibits strong reflectance in the near-infrared spectrum, a characteristic effectively captured in the infrared imagery and translated into each radiance field model. The use of infrared imagery foregrounds SHARP's operational capabilities beyond true color imagery, extending into the domains of remote sensing and technical imaging. The images were captured at two locations in Dublin, Ireland: the National Botanic Gardens (Site 1; 09.02.2026) and Killiney Hill Park (Site 2; 11.02.2026). Preprocessing of raw image files to JPEG format was performed using the open-source photography application darktable. The data encompass multiple spatial scales, combining interior and exterior environments from close-range detail views to expansive landscapes.

Based on the SHARP GitHub repository (APPLE 2025), we developed a local Jupyter Notebook implementation (JUPYTER DEVELOPMENT TEAM 2026) to structure installation and data processing tasks. The Notebook facilitates systematic batch processing: each image in the input directory is processed individually and exported to the output folder as a radiance field representation in .ply format. On a conventional laptop (Intel Core Ultra 7, 32GB RAM, RTX 4060 Laptop GPU), inference required only a few seconds per image, enabling efficient processing across image collections. For the visualization and further engagement with the resulting models, we used SuperSplat Editor (PLAYCANVAS LTD. 2026) and the KIRI 3DGS add-on (KIRI INNOVATIONS 2026a) for Blender (BLENDER FOUNDATION 2025).

The resulting radiance fields unfold as complex 3D scenes with structural coherence beyond the captured views of the input data. We observe that the visual and spatial coherence appears to be relatively higher in close proximity to the original camera position, with increasing uncertainty toward more distant regions of the scene. The consistent alignment of the reconstructions to absolute metric scale is one of the more impressive features of SHARP. In our implementation, the reconstructions maintain the dimensions of their target systems at the meter scale, enabling seamless combination of models derived from different images. Specific to monocular view synthesis, SHARP excels at capturing the intricate organic complexities of vegetation, while occasionally exhibiting limitations in resolving thin linear structures, such as pipes, columns, or branches. Rather than generating isolated geometric objects, SHARP produces concentrations of spatial information, shifting how landscape entities are identified and engaged.

The utility of SHARP was additionally tested in a landscape architecture studio at University College Dublin (UCD), where students explored SHARP as part of their design projects. Within the studio, we explored a wide range of inputs, including smartphone images, land-

scape paintings, historic photographs, and game engine captures, across which SHARP reliably generated coherent 3D environments. The students used the reconstructions to navigate the virtual scenes, identify and measure features, describe their spatial relations, and produce stylized renderings. The combination of reconstructions of the same scene from different time periods enabled an exploration of temporal changes. In Ireland, where access to public geospatial data is limited, SHARP proved particularly useful by providing custom, case-specific data, enabling students to engage with situated conditions that would otherwise be difficult to model or assess. Within this context, SHARP provides an alternative framework for sensing and modeling sites that is easily accessible to students and highly applicable to landscape architecture.

Fig. 5: SHARP-generated radiance field within a greenhouse at the National Botanic Gardens (Site 1). The lower-left region reveals the underlying 3D Gaussian splatting structure of SHARP within the foliage.

4 Discussion: Situating SHARP and Spatial Artificial Intelligence

SHARP engages landscapes as situated visual-spatial encounters rather than spatially exhaustive environments. The inferred digital landscapes function as probabilistic spatial propositions conditioned by learned visual priors that articulate plausible spatial organizations with maximal inference from minimal input. These reconstructions combine the visual fidelity of radiance fields with the spatial precision and metric scaling inherent to lidar sensing, maintaining local coherence while becoming increasingly indeterminate beyond the immediate context of inference.

SHARP internalizes visual and spatial relationships present in extensive training data, embedding them within the parameters of the model rather than deriving them explicitly from

the input image. Similar to human visual perception of spatial dimensions, SHARP interprets visual cues, such as texture gradients, material granularity, relative size relationships, atmospheric attenuation, and spatial frequency patterns, to transmute gridded brightness values into a complex 3D scene. While the training stages and internal reasoning of SHARP remain inaccessible to its users, SHARP effectively collapses a multi-stage process of sensing, processing, verification, scaling, and visualization into a one-click application – inference replaces measurement. SHARP provides access to advanced digital models for users not conventionally involved in the technical aspects of sensing and modeling in remote sensing and computer vision, but rather in the aesthetics of landscape photography.

SHARP is one instance within a broader proliferation of sensors and models, each generating situated and partial captures of their target systems and each requiring evaluation with respect to the particular aspects, assumptions, and operational conditions through which they render landscapes legible. For radiance fields and Gaussian splatting representations, evaluation metrics may differ substantially from those used in preceding gridded or point-based methods and data structures. In alignment with previous technological categorizations, such as lidar remote sensing, photogrammetric processing, and point cloud representations, the emergence of radiance field models must be recognized as a distinct and proliferating category for modeling and representing landscapes. This consolidates emerging conceptions of radiance fields into a coherent discussion within landscape architecture.

SHARP generates 3D Gaussian splatting representations, an implementation of radiance field models, which themselves constitute part of an expanding domain of spatial artificial intelligence (PAPADIMITRIOU 2025). Their emergence signals a shift in how 3D landscape models are produced, accessed, and mobilized within design disciplines. The sensing and modeling of landscapes become near-instantaneous and quasi-intuitive processes, less constrained by heterogeneous sensor configurations, fragmented data collections, inaccessible software packages, and specialized expertise outside of the field of landscape architecture. This implies a structural reorientation in the role of digital models within landscape architecture: from manual acquisition, verification, and modeling toward embedded, accessible, visually-grounded, spatial engagements.

This evolution points to the emergence of world models, in which formerly distinct domains, such as computer vision, simulation, and geospatial analysis, are increasingly consolidated within a unified computational framework. Drawing on the logic of the bitter lesson (SUTTON 2019), contemporary artificial intelligence research suggests that the intermediate representations and task-specific heuristics that once structured fields like computer vision and digital reconstruction are becoming epistemically peripheral (SITZMANN 2026). Conceptions of 3D modeling are shifting from the production of explicit geometric representations toward the internalization of spatial structures within scalable world models, reframing geometric operations, classification, and rendering as transient scaffolds rather than epistemic endpoints. Consequently, the role of landscape architects shifts from managing fragmented technical procedures toward configuring and directing models that internalize the multi-modal organization of physical environments as coherent, operative systems. SHARP, therefore, represents more than a technical addition to an expanding collection of models driven by artificial intelligence, marking an early manifestation of a broader convergence within sensing and modeling of the Earth.

Fig. 6: SHARP-generated radiance field of an expansive landscape view at Killiney Hill Park (Site 2), capturing the extended terrain and distant horizon, to demonstrate large-scale spatial coherence and atmospheric depth

5 Conclusions

This paper has demonstrated how radiance fields, instantiated through SHARP, operate as inference-based landscape models capable of generating metric-scale, spatially coherent environments from minimal input. By situating SHARP within a broader categorization of radiance fields and validating its application through model explorations and pedagogic experiments, the paper clarifies the role of spatial artificial intelligence as an emerging operative paradigm in landscape architecture. Rather than replacing established sensing and modeling processes, these models shift the emphasis from exhaustive measurement and uniform sampling toward situated, probabilistic, and experiential forms of spatial reasoning.

The emergence of radiance fields represents a significant advance in landscape modeling, offering a more immersive experience than established digital approaches. Unlike point clouds, triangles, vectors, and related geometric reconstruction methods, radiance fields capture complex atmospheric conditions essential to visual perception, including volumetric brightness, color, and transparency, specular reflections, and dynamic light scattering. This suggests latent potential within the technology, a phenomenological surplus, by which the model captures the ephemeral qualities of experience and encounter relevant to landscape architecture. As such, radiance fields serve as modeled propositions that mediate sensing, inference, and spatial experience. Recognizing this capacity has value for landscape architects, as it elevates the digital model from a static representational surrogate to a means of more closely articulating the complex, shifting conditions within its target system.

This development marks a shift from procedural, competency-dependent toward quasi-intuitive, near-instantaneous modes of landscape modeling. While access to advanced tools and

methods remains a constraint in landscape modeling, novel approaches synthesize previously disparate processes and their associated requirements for specialized knowledge, effectively lowering the threshold for engaging landscapes through complex forms of representation. While this transition is neither complete nor immediate, its potential is already evident in practice and can now be articulated in a methodologically grounded, scientifically substantiated manner.

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A Prompt-to-Image Workflow for Professional Planting Visualisation: Evaluating the Use of ChatGPT-4o in Landscape Architecture

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Abstract: Visualising planting concepts requires images that are botanically legible, spatially coherent, and seasonally plausible. While recent multimodal AI systems promise rapid, context-aware visualisations, reproducible workflows grounded in real planning data remain scarce. This paper proposes and tests a prompt-to-image workflow developed by the author for planting visualisation using ChatGPT (Version GPT-4o) (OpenAI 2025) in a realised project in Paris, based on a planting plan, species list, licence-free plant reference images, and a vegetation-free context perspective. The workflow combines structured data extraction (JSON content profile), a modular prompt architecture with documented versions (v0-v2), and image generation constrained to a red-marked target zone. Five images were generated under constant inputs to document system-immanent variability; the most plausible variant was selected as evaluation stimulus (Image A, Fig. 4). Seven experts assessed Image A using Likert ratings, an error checklist, and qualitative comments. Results indicate limited suitability for professional, species-specific planting communication (overall mean 2.34/5), with key limitations in botanical identity, morphology, phenology, and geometric scale rather than inpainting artefacts. The contribution is a clearly documented workflow and an expert-based delimitation of current use boundaries.

Keywords: Planting design, visualisation, generative AI, prompt-to-image, reproducibility, landscape architecture

1 Introduction

Visual communication of planting concepts is central to landscape architectural design, coordination, and decision making. Between hand sketch, collage, and CAD-based representation, images are an essential tool for design communication and collaboration (Rekittke & Hayles 2025, 636). For planting design, this task is particularly demanding: visualisations must remain botanically legible while conveying seasonal atmosphere and spatial structure.

Traditional visualisation techniques such as analogue drawings, Photoshop collages, or CAD drawings/renderings are well established but often time-consuming and limited in atmospheric expressiveness, especially for complex multi-layered plantings. Recent studio and practice reports highlight both the creative potential and the limitations of generative AI, particularly decreasing controllability and reproducibility as task complexity and detail increase, and a continued need for human intervention when precision is required (Zwangsleitner et al. 2024, 992, Schroth & Maier 2025, 665).

Multimodal AI models such as ChatGPT-4o (OpenAI 2025) can combine planting plans, species lists, and reference images to generate context-aware visualisations very quickly. However, reproducible workflows grounded in real planning data and systematic expert evaluations of the resulting images remain scarce. This paper specifies a prompt-to-image workflow for planting visualisation and empirically assesses a curated AI output against professional criteria.

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Research question: To what extent can a ChatGPT-4o-based workflow generate planting visualisations that are botanically and spatially accurate and atmospherically convincing?

Objectives:

- document a reproducible workflow (JSON content profile, modular prompts, constrained inpainting, controlled variant generation),
- define and structure evaluation criteria (ratings, error checklist, coded comments) across botany/geometry, atmosphere, and applicability,
- identify error patterns and boundaries for responsible professional use.

The paper contributes to the DLA theme *"Computation and Digital Technologies"* by offering a transparent, reproducible account of how multimodal AI can be embedded in planting visualisation workflows while critically discussing the limitations, risks, and professional responsibilities associated with presenting AI-generated images as "professional standard."

2 Related Work

Research and practice on AI-based visualisation in landscape architecture can be grouped into three strands that form the background for this study:

1) explorative uses of image generation in education and early design,
2) data-driven models for vegetation and planting layouts,
3) empirical studies on the adoption of AI tools in professional offices.

Explorative image generation in studios and teaching
Several recent contributions report how text-to-image systems are introduced in design studios and seminars. Rekittke & Hayles (2025) describe early experiments with Midjourney and similar tools in landscape architecture education. They show how AI images can support conceptual exploration, while also revealing limits in producing drawing-like, scaled outputs and in maintaining historical and spatial logic (REKITTKE & HAYLES 2025, 640-641). Florian Zwangsleitner et al. (2024) report on a master-level seminar combining analogue models, digital workflows and AI prompting. While students appreciated the speed and atmospheric richness of AI images, the authors emphasise decreasing reproducibility and controllability as the level of detail increases technical plans and exact planting layouts remained firmly in the domain of CAD and image editing (ZWANGSLEITNER et al. 2024, 992).

Data-driven and model-based approaches to vegetation
A second strand of research explores the use of machine learning and generative models for vegetation pattern generation. Xun Liu et al. (2024) experiment with GAN and pix2pix architectures to derive planting patterns from environmental data such as relief, soil and climate. Their work suggests that data-driven models can produce ecologically plausible distributions but it also underlines the need for ecological validation and specialist knowledge in training and interpreting the models (LIU et al. 2024, 204-206). In contrast to these approaches, the present paper does not aim at AI-driven or data-driven generation of planting layouts. Instead, it assumes a fixed, professionally designed planting plan and focuses on visual communication of this plan through AI-generated imagery.

Professional adoption and concerns
A third body of work examines how practitioners perceive and integrate AI in their everyday workflow. Braiden et al. (2025) present a large survey among landscape architects in North

America. Almost half of the respondents report using AI tools, mostly for text drafting, concept sketches and early visualisations. However, usage drops markedly in later phases such as planting and construction planning. Respondents express concerns regarding data security, copyright, error and the risk of miscommunication when AI-generated images are taken at face value by clients or other stakeholders (BRAIDEN et al. 2025, 628-629). Schroth and Maier (2025) describe generative AI as efficient, but constrained by limited precision and control, implying a continued need for careful human oversight in professional contexts (SCHROTH & MAIER 2025, 665, 674). Concerns about trust, liability, and stakeholder misinterpretation are also reflected in practitioner surveys (BRAIDEN et al. 2025, 629).

Yet, they also reveal a clear research gap: there is little work that links AI image generation to concrete planting plans and species lists, documents the prompt and parameter structure in a reproducible way, and evaluates the resulting images systematically with domain experts. The present study addresses this gap by proposing a JSON-based prompt-to-image workflow and an expert evaluation focusing on botanical/spatial accuracy, atmosphere and conditions for professional use.

3 Methodology

3.1 Overall Approach

This study uses a mixed-methods design that combines structured analysis of real-world planning data, development of a reproducible prompt-to-image workflow using ChatGPT (Version GPT-4o), and an expert assessment using standardised Likert ratings and qualitative responses analysed with a qualitative content analysis approach following Mayring (2015). ChatGPT (Version GPT-4o) was used for workflow specification, prompt development, and image generation only. Participant recruitment, data collection, rating aggregation, qualitative coding, and interpretation were conducted without AI (OPENAI 2025).

The study addresses the research question: ***To what extent can a ChatGPT-4o-based prompt-to-image workflow generate planting visualisations that are botanically and spatially accurate and atmospherically convincing when grounded in real planning data?***

3.2 Case Study and Planning Data

The empirical basis is a realised project in Paris, designed by a Berlin-based landscape architecture office. The office provided complete planning documents for the planting area evaluated in this study. No fictional or synthetic planning data were introduced.

The workflow was based on the following input datasets:

1) Planting plan (Fig. 1)
   Symbolic plan representation including species allocation, matrix/island structure, and density patterning.
2) Species list
   Botanical names (including cultivar where applicable), plant quality specifications (e. g., multi-stem vs. standard where provided), quantities, habitus-related notes, and additional remarks on establishment and seasonal characteristics.

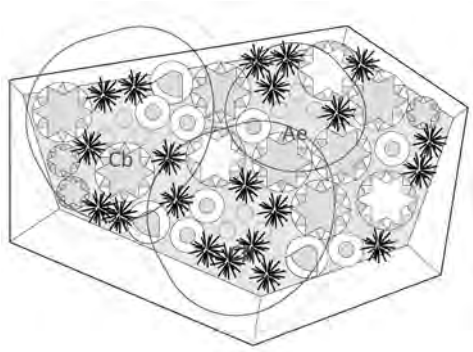

Fig. 1:
Planting plan out of the real project

3) Reference plant images
One to three representative images per species, used as morphological references for the target appearance (leaf size/shape, typical habit, texture). These images served as reference material for the generation process; they were not used as evaluation stimuli.

4) Context perspective (vegetation-free base image; Fig. 2)
A vegetation-free JPEG exported from a 3D model, used as the geometric and photographic base for inpainting. The view corresponds to an approximate eye height of 1.5 m and an approximate focal length of 35 mm. The hardscape background (walls, planter geometry, ground plane) was treated as fixed and was not to be altered during generation.

5) Seasonal target condition
Midsummer (July), representing fully developed foliage.

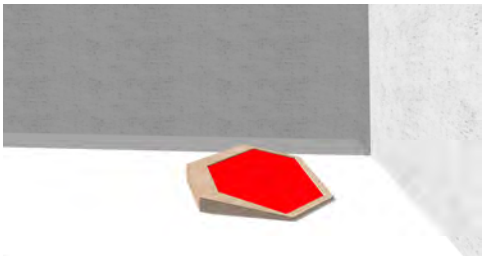

Fig. 2:
Context perspective without vegetation and red region of interest

3.3 Workflow Development (Fig. 3)

The prompt-to-image workflow was specified to translate real planting design data into a controlled visualisation within a fixed project context. The workflow was developed by the author for this study to formalise and document prompt engineering steps from real planning data to constrained image generation. The workflow comprises two consecutive layers: (A) a meta-prompt layer (v0-v2) used to elicit, validate, and formalise project inputs into a JSON content profile, and (B) an operational generation layer that converts this profile into a fixed-order inpainting prompt for image output. It follows a seven-step structure (Fig. 3) and is designed so that each stage can be documented and repeated.

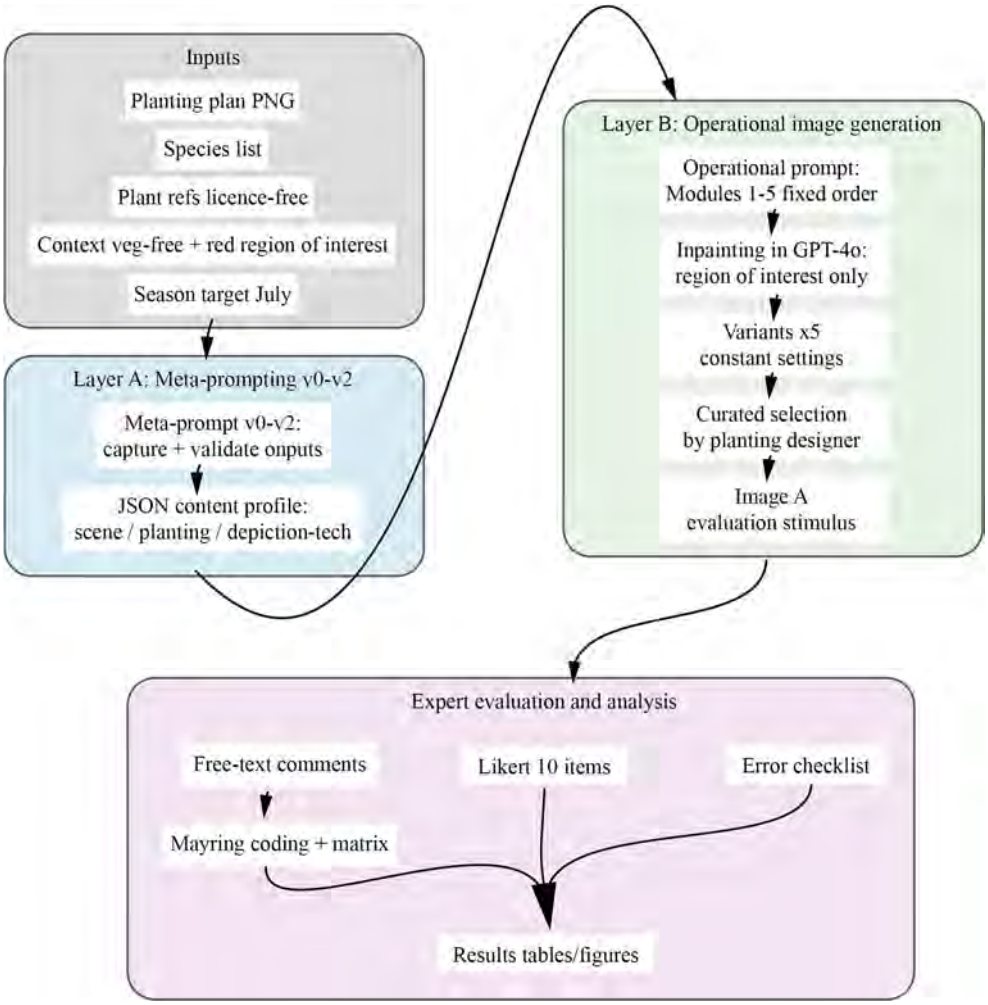

Fig. 3: Workflow development including methodology

1) Data ingestion (Layer A)
   The planting plan, species list, licence-free reference plant images, and the vegetation-free context perspective were collected as the input dataset (Section 3.2). The context perspective contained a red-marked target area indicating the planting zone to be visualised.
2) Structured data extraction (Layer A)
   Planting information was compiled from the planting plan and species list, including species identity, intended vertical layering (matrix/islands/shrubs/trees), and relevant habitus cues. The licence-free reference plant images were used to derive morphological descriptors (e. g., leaf character, typical habit) to support the subsequent structured description.

3) Creation of a JSON-based content profile (Layer A)
   The extracted planning information was encoded into a structured JSON content profile capturing scene parameters (camera and seasonal target), planting composition and layering, and style and technical requirements (Section 3.6). The JSON content profile functioned as the stable, machine-readable input basis for prompt construction.
4) Prompt construction using modular prompt blocks (Layer B)
   A modular prompt architecture was used to separate planning logic (species composition and spatial/layering intent derived from the JSON profile) from depiction logic (style, atmosphere, and technical instructions). The prompt modules and their assembly are specified in Section 3.5.
5) Image generation via inpainting guided by the red-marked target area (Layer B)
   Image generation was performed in ChatGPT (Version GPT-4o) using the vegetation-free context image as the fixed base. The red-marked target area in the context image served as the sole generation zone. The prompt included an explicit rule to generate vegetation only within the red-marked area and keep all non-marked areas (hardscape, walls, planter geometry, ground plane) unchanged.
6) Iterative prompt precision adjustments (Layer B)
   A small number of targeted prompt adjustments were made during workflow finalisation to reduce unintended changes outside the target area and to stabilise key planting hierarchy cues (see Section 3.8 for the documented adjustment log). Adjustments were limited to specific modules while the remaining prompt structure was kept stable.
7) Production under constant conditions: Five images were generated under constant inputs and settings to document system-immanent variation (Section 3.9).

3.4 Prompt Architecture, Versioning, and Assembly (v0-v2)

Prompt versions v0-v2 refer to the meta-prompt used for project capture and parameterisation. They are distinct from the operational generation prompt that produces the images. To ensure transparent control of image generation, a modular prompt system was used and documented in three stages (v0-v2). v0 defines the prompt baseline (required input data and the domain-specific objective). v1 adds an interactive procedure for structured data elicitation (follow-up questions and interim summaries). v2 denotes an initial/meta-prompt that systematises data elicitation, validation, and the subsequent assembly of the generation prompt. v2 yields a JSON content profile as the structured data basis and an operational generation prompt derived from it. Thus, v2 governs data acquisition and prompt assembly, whereas the operational generation prompt controls the image output only.

v0 specified required inputs and the domain objective (species-specific planting visualisation within a fixed context image). v1 added an interactive elicitation routine (mandatory follow-up questions on camera, season, planting layers, and negative criteria) and interim validation summaries. v2 formalised a structured output schema (JSON content profile with fixed keys for scene/planting/style) and a fixed assembly rule that maps JSON fields to the five operational prompt modules (Modules 1-5), including the region of interest constraint as a mandatory technical rule.

ChatGPT (Version GPT-4o) was used for prompt development (v0-v2) and multimodal image generation (OPENAI 2025). Plant references consisted exclusively of licence-free images and were used only as morphological cues. The operational generation prompt was organised

into five modules and always assembled in a fixed order: scene/perspective, planting description, depiction style, season/light, and technical instructions including negative criteria. The generation area was not defined via a black-and-white mask; instead, it was specified by a red-marked target zone in the context image (generate only within the marking; keep all other image areas unchanged).

Key excerpts from the final meta-prompt (v2), including the fixed module structure and control rules, are provided in Box 1.

Box 1: Excerpts from the Final Meta-Prompt (v2, Modular Structure)

Scene & perspective: "Use the provided vegetation-free courtyard perspective as fixed base (eye height ~1.5 m, ~35 mm). Do not change walls, planter geometry, or ground plane."

- Planting structure: "Depict the planting strictly according to the species list and layered logic (matrix / islands / shrubs-trees), using the provided reference images as morphological cues."
- Style: "Specify the intended depiction style (e. g., photorealistic) and require realistic shadows and clear species separation."
- Season & light: "Specify target season and lighting (here: midsummer/July; soft evening light) as fixed depiction parameters."
- Spatial rule (target zone): "Generate vegetation only inside the red-marked planting area in the context image; keep all non-marked areas unchanged."
- Negative criteria: "No people, furniture, vehicles, additional objects; avoid painterly looks, oversaturation, repetition artefacts, distortions, unrealistic plant forms."

3.5 Derivation of the Generation Prompt from v2

The operational inpainting prompt was assembled from the validated JSON content profile using a fixed module order (scene/perspective; planting; depiction style; season/light; technical constraints and negatives). The depiction parameters (photorealistic; July; soft evening light) and the region of interest rule were held constant for the generation of the variants. Any refinements were limited to individual modules and logged (see Section 3.8).

3.6 JSON Content Profile (Result of Data Extraction and Analysis)

The JSON content profile provides the structured data basis for image generation. It was created after reviewing and cross-checking the planting plan, species list, licence-free plant reference images, and the vegetation-free context perspective, and it encodes all planning information relevant for visualisation in a machine-readable format. The profile serves three purposes: consistent transfer of key design parameters into the prompt modules, separation of planning logic (species, layering, distribution, scale) from depiction logic (style, lighting, season), and transparent documentation of inputs to support reproducibility.

The profile comprises three levels:

1) Scene (camera/perspective parameters, target season, lighting assumptions),
2) Planting (matrix/island logic, species lists by vertical layer, optional height/habitus attributes),
3) Depiction/Technical settings (depiction style, desired depth effect, aspect ratio).

An excerpt of the resulting JSON content profile, which serves as the stable input for prompt assembly, is shown below.

JSON Content Profile (Excerpt, Full Version Documented in the Project Archive):

```
{
  "scene": {
    "camera": {"focal_length_mm": 35, "eye_height_m": 1.5},
    "season": "July",
    "lighting": "soft evening light"
  },
  "planting_area": {
    "matrix": {"species": "Hakonechloa macra", "coverage_pct": "60-80"},
    "islands": [
      {"species": "Rodgersia podophylla", "height_cm": "60-100"},
      {"species": "Podophyllum 'Spotty Dotty'"}
    ],
    "shrubs_trees": [
      {"species": "Aralia elata", "form": "multi-stemmed"},
      {"species": "Catalpa bignonioides", "leaf": "large cordate"}
    ]
  },
  "style": {
    "mode": "photorealistic",
    "depth_of_field": "soft",
    "color_profile": "natural midsummer greens"
  }
} (Version ChatGPT-4o) (OpenAI 2025)
```

An excerpt of the operational inpainting prompt used for the five constant-condition generation runs is provided in Box 2.

Box 2: Operational Generation Prompt (Excerpt):

“A polygonal raised wooden planter … neutral architectural background … focus on the planting structure inside the raised bed … multi-layered planting (upper layer / climbers / mid & ground layers) … ultra-detailed photorealistic planting rendering … midsummer … soft evening light …”
“Generate vegetation only inside the red-marked target area; do not alter concrete walls, wooden planter, or ground plane.”
“Avoid repetition artefacts, distortions, unrealistic plant forms. Negative prompt: exclude people, furniture, cars, artificial objects, over-saturation, painterly effects.”

(*Note: The full operational prompt is documented in the project archive; only a short, verifiable excerpt is shown here* (OpenAI 2025).)

3.7 Image Generation within the Red-Marked Target Zone

Image generation was performed with ChatGPT (GPT-4o) using the vegetation-free context perspective as fixed base image. The planting area was constrained by a red-marked region of interest. The operational prompt enforced the rule to generate vegetation only inside this region and keep all non-marked areas unchanged. No manual post-processing (e. g., Photoshop retouching) was applied to the generated variants. The selection of Image A was based on plausibility review only (see Section 3.10).

3.8 Documented Prompt Refinements

During the development of the final prompt, a few targeted refinements were made and systematically logged to differentiate stable elements from newly introduced stabilising constraints:

1) Vertical hierarchy of a woody species: Following feedback on the intended dominance in the upper vegetation layer ("Catalpa slightly taller"), the planting description was extended with an explicit height/crown specification to reinforce the intended hierarchy.
2) Stabilisation of the non-vegetated context: After an unsatisfactory output the technical module was tightened to prevent changes outside the planting area (keep existing geometry unchanged; generate vegetation only within the target zone).
3) Target-zone rule as a standard constraint: The coupling of the generation area to the red marking in the context image was formalised as an unambiguous rule and adopted as a standard element of the final prompt.

These adjustments should be understood as minimal interventions to improve controllability, without modifying the underlying data basis (planting plan, species list, reference images).

3.9 Image Generation under Constant Conditions (Five Outputs)

To capture system-immanent variability, five outputs were generated under constant settings. Across all five outputs, the following elements were kept identical: the vegetation-free context image (JPEG), the red-marked target zone as spatial constraint, the JSON content profile (final version), the prompt-module order (1-5), and depiction parameters for style, season, and lighting (photorealistic visualisation; midsummer condition; soft evening light). Negative criteria were also held constant across outputs (e. g., no people, furniture, or additional objects; no painterly effects; no oversaturation; no obvious repetition patterns) (Figs. 4-8).

Stochastic effects of generation (e. g., non-fixable random initialisation/seed in the utilised system) could not be controlled deterministically. Differences between the five outputs are therefore treated as system-immanent variance and made transparent through repeated generation.

Figs. 4-8:
Five image variants based on the same prompt (from top left to bottom left) (Version GPT-4o, OPENAI 2025)

3.10 Curated Test Image

For the expert evaluation, a curated test image (Image A, Fig. 4) was defined as the standardised stimulus. From the five images generated under constant conditions, the person responsible for the realised planting design selected the variant that most plausibly represented the intended species composition, vertical layering, and midsummer effect. This selection serves as a practice-oriented safeguard to ensure that the evaluation stimulus is not dominated by a singular outlier (e. g., strong artefacts), but represents the most plausible image under identical conditions.

3.11 Expert Evaluation

The curated AI image (Image A, Fig. 4) served as the standardised stimulus for the expert evaluation (n = 7). The evaluation comprised ten itemised Likert ratings (1-5) covering Botany/Geometry (4 items), Atmosphere (4 items), and Application (2 items); short free-text comments; and an error checklist (none/low/mid/high) plus an overall frequency judgement (rare/sometimes/often).

Free-text comments (n=6) were segmented into meaning units (n=53; one unit = one discrete statement, sentence or clause). A deductive coding scheme was derived from the evaluation framework (Botany/Geometry, Atmosphere, Application) and the predefined error checklist, resulting in a codebook of main categories and sub-codes (MAYRING 2015, 97). Multiple coding of a meaning unit was allowed where a statement addressed more than one aspect. Coding was performed by the author; a second pass was used to check internal consistency. The full coding matrix is documented in the project archive. For transparency, the coding matrix documents all coded units and category assignments (53 meaning units from 6 participants; 11 main categories; multiple coding allowed, resulting in 86 category assignments) (documented in project archive).

4 Results

4.1 Sample Characteristics

Seven participants completed the evaluation (n=7). Reported roles were: landscape architecture practice (n=2), research/teaching (n=2), and dual role "both" (n=3). Countries reported were Germany (n=3), Switzerland (n=1), Austria (n=1), Germany/Switzerland (n=1), and one missing country entry (n=1). Professional experience ranged from 2 to 25 years (median 12). Six participants provided qualitative comments in at least one free-text field (n = 6), while one participant submitted only the Likert ratings (n = 1).

Qualitative comments were segmented into meaning units (n = 53) and coded deductively (MAYRING 2015). Table 1 summarises the main categories by number of meaning units assigned, number of contributing participants, and code assignments (multiple coding allowed).

Table 1: Main category summary of qualitative coding following Mayring: meaning units (n), participants (n), and code assignments

Main category	Meaning units (n)	Participants (n)	Code assignments (n)
Botanical accuracy	14	6	21
Professional applicability	9	6	12
Visual realism	8	4	10
Spatial structure	7	4	9
Professional risk / no-go	8	5	8
Lighting/depth	5	5	6
Future work	5	5	5
Seasonality	5	5	5
Matrix legibility	4	4	4
Uncertainty	4	2	4
Professional risk / miscommunication	2	2	2

Note. Participants (n) refers to commenting participants (n = 6). A total of 53 meaning units were coded; multiple coding is possible, so category totals can exceed 53. Of the 12 predefined main categories in the codebook, 11 occurred in the material.

These three indicators help summarise the qualitative material: meaning units reflect topic density, contributing participants show how widely a theme was shared, and code assignments capture recurrence under multiple coding. In this form, Table 1 provides a compact evidence base for which qualitative themes dominated the expert feedback and how consistently they occurred.

4.2 Rating Outcomes for Image A (Likert 1-5)

Only Image A was assessed with itemized Likert ratings (10 items, scale 1-5; 1 = very poor, 5 = excellent). Across all items, the mean score was 2.34/5 (median 2.20). The three predefined dimensions yielded the following mean scores:

- Botany/Geometry (4 items): 2.21/5
- Atmosphere (4 items): 2.64/5
- Application (2 items): 2.00/5

4.3 Botanical and Spatial Accuracy

Image A was rated on four botany items (Likert 1-5). Mean scores were 2.29 for species identity, 1.86 for morphology, 2.00 for habit & layering, and 2.71 for matrix readability (Tab. 2). Identity, morphology, and habit/layering showed consistently low distributions (≤ 2 by 5/7 participants; 71%), while matrix readability was rated 3 by 5/7 (71%). Comments emphasised coarse recognisability ("*Genus is recognizable, but species and cultivars are not*", P1, translated) and insufficiently differentiated plant structure ("*same stem form across different species*", P6, translated). Several remarks also referenced mismatches in vertical hierarchy (canopy–understorey relations), suggesting that spatial planting logic was not consistently maintained.

Table 2: Likert ratings for Image A by dimension and item (n = 7; scale 1-5 scale, 1 = very poor, 5 = excellent; reported as mean and share of low (≤2) and high (≥4) ratings)

Dimension	Item	Mean	% ≤ 2	% ≥ 4
Botany	Species identity	2.29	71.4	28.6
Botany	Morphology	1.86	71.4	0.0
Botany	Habit & layering	2.00	71.4	0.0
Botany	Matrix readability	2.71	28.6	0.0
Atmosphere	Seasonality	2.86	42.9	28.6
Atmosphere	Lighting	3.00	28.6	28.6
Atmosphere	Depth	2.71	42.9	28.6
Atmosphere	Overall atmosphere	2.00	71.4	14.3
Application	Communication value	2.43	71.4	28.6
Application	Professional trustworthiness	1.57	71.4	0.0

4.4 Atmospheric Quality

Atmospheric quality was assessed with four Likert items (1-5). Mean scores were 2.86 for seasonality, 3.00 for lighting, 2.71 for depth, and 2.00 for overall atmosphere. Ratings

showed a split: lighting clustered at 3–4 (5/7; 71%), whereas overall atmosphere concentrated at 1-2 (5/7; 71%). Comments mirrored this pattern, with some participants finding depth/lighting convincing ("*depth and lighting are good and convincing*", P4, translated) and others noting limited spatial impression or inconsistencies ("*hardly any depth*", P3; "*shadows seem inconsistent*", P6, translated). Overall, local rendering cues performed better than the holistic atmospheric impression.

4.5 Practical Applicability and Professional Standard

Mean scores were 2.43 for communication value and 1.57 for professional trustworthiness (Likert 1-5). Trustworthiness was rated 1 by 5/7 participants (71%), whereas communication value clustered at 2 in 4/7 cases (57%). Comments emphasised limited client-facing usability ("*I would not go to a client with this*", P2, translated) and described use primarily for conveying mood to non-experts (P3). One participant noted process constraints, stating that complete planting plans and species lists are often available only late in execution planning (P4). Overall, perceived applicability was constrained by low professional trust and workflow timing.

4.6 A/B Preference (Image A vs. Baseline B)

All participants preferred the baseline visualisation (Image B; Fig. 9) over the AI-based visualisation (Image A; Fig. 4) (**B chosen by 7/7; 100%**).

Preference reasons most frequently referred to higher perceived realism and depth in B, and clearer recognizability of plant habit and hierarchy. Representative statements include: "***more realistic, has spatial depth and high recognizability of plants***" (P3, translated), "***sterile and smooth… B has more depth and looks more realistic***" (P4, translated), and "***better depiction of habitus and hierarchy; better spatial impact***" (P1, translated).

Fig. 9:
Visualisation from the real project served as a baseline and was created conventionally using Photoshop collage

4.7 Error Checklist (Intensity and Frequency)

Participants assessed predefined error types using four intensity levels (none/low/mid/high) and reported overall frequency (rare/sometimes/often). Across participants (n=7), the highest mean severities (coded 0-3 for aggregation) were observed for phenology error (mean 2.00), species confusion (mean 1.86), and geometric scale error (mean 1.57). Intermediate severities were recorded for foreign objects (mean 1.29) and oversaturation/colour shift (mean 1.29), while density/distribution was lower (mean 1.14). Inpainting artefacts showed the lowest severity (mean 0.43) (Tab. 3).

Table 3: Error checklist for Image A (n = 7): mean severity scores (0-3) and share of ratings by intensity level (% high, % mid+high)

Error type	Mean severity (0-3)	% high	% mid+high
Species confusion	1.86	42.9	71.4
Geometric scale error	1.57	14.3	71.4
Phenology error	2.00	42.9	71.4
Density/distribution	1.14	14.3	28.6
Inpainting artefacts	0.43	0.0	0.0
Foreign objects	1.29	14.3	57.1
Oversaturation / colour shift	1.29	14.3	42.9

Intensity distributions illustrate the contrast between error types: inpainting artefacts were rated none by 4/7 participants and low by 3/7 (0/7 mid or high). By comparison, species confusion was rated high by 3/7 and phenology error was rated high by 3/7.

Overall problem frequency was reported as often by 3/7, sometimes by 2/7, and rare by 2/7 participants.

5 Discussion

The evaluation indicates that the AI-generated planting visualisation (Image A) does not meet a professional standard for species-level planting representation in its current form. This is evidenced by low botany/geometry ratings (mean 2.21/5) and consistently low scores for species identity, morphology, and habit/layering (each rated ≤2 by 71% of participants). In parallel, the error checklist shows the highest severities for phenology error (mean severity 2.00/3), species confusion (1.86/3), and geometric scale error (1.57/3). Overall, the quantitative findings match the qualitative statements that recognition is often limited to the genus level, with species and cultivars remaining indistinguishable ("*genus recognizable, but species and cultivars are not*", P1 translated) and that plant structure is insufficiently distinctive ("*same stem form across different species*", P6 translated). Notably, the dominant botanical and geometric error types identified in the ratings and checklist emerged despite the workflow's control measures (JSON-based input structuring, fixed module order, red-marked target-zone-only inpainting, and constant negative criteria across five generation runs; Sections 3.3-3.6), indicating that, within this configuration, semantic plant fidelity and scale relations, rather than typical inpainting artefacts, were the primary limitations.

A key implication is that "plausible planting" in a visual sense should not be conflated with botanical correctness or spatial correctness. While lighting and some local depth cues received comparatively higher ratings (lighting mean 3.00/5; depth mean 2.71/5), overall atmosphere remained low (mean 2.00/5), and participants overwhelmingly preferred the non-AI baseline (Image B; 7/7). Within the photorealistic configuration tested here, the images can appear visually convincing while still containing systematic botanical and geometric errors. This limits their reliability when accurate, detailed species identification, growth form, seasonal state, and scale relationships are critical.

From a professional and ethical perspective, the observed error profile implies a high risk of miscommunication if AI images are used without safeguards in contexts where planting decisions have contractual, ecological, or cost consequences. The low trustworthiness ratings (mean 1.57/5; 71% rated 1) and explicit participant constraints ("*I would not go to a client with this*", P2, translated) indicate that, under the conditions evaluated in this study (GPT-4o model version and the documented prompting and workflow configuration), AI images should not be used as stand-alone evidence for execution-related deliverables (e. g., planting specifications, procurement, maintenance instructions, or construction coordination). In competition or participatory settings, several statements point to disclosure expectations ("*transparency that this is AI-based*", P6 translated), which aligns with the need to prevent stakeholders from interpreting AI images as faithful depictions of specified species, seasonal effect, or spatial proportions.

A limited use case remains plausible under strict framing as an early-stage, low-stakes communication artifact to explore spatial mood or support discussions with non-expert audiences. This requires clear AI labelling, an explicit statement of the intended level of botanical fidelity, and a domain review cross-check against the planting plan and species list. In this study, the low severity of inpainting artefacts (mean 0.43/3) suggests that typical "image editing" artefacts were not the dominant limitation; rather, the limiting factors were primarily semantic plant fidelity (identity, morphology, phenology) and spatial consistency (scale and layering). Accordingly, future technical improvements should prioritize constraint-based control of plant identity and seasonal state, as well as explicit anchoring of geometric scale and vertical hierarchy.

Despite the limited image-level performance in this GPT-4o-based setup, the JSON content profile and modular prompt architecture provide a reusable structure for integrating planning data and documenting constraints in AI-assisted visualisation workflows. However, the present findings reflect a specific model–workflow configuration; replication should therefore compare both updated models and revised prompting protocols under transparently versioned specifications.

6 Conclusion and Outlook

This study evaluated a prompt-to-image workflow for AI-based planting visualisation in a single realised project context with an expert sample (n = 7). The AI-generated image (Image A, Fig. 4) achieved an overall mean rating of 2.34/5 across 10 Likert items (1-5), with comparatively low performance in Botany/Geometry (2.21/5) and Application (2.00/5). Professional trustworthiness was the weakest application criterion (mean 1.57/5; 5/7 participants rated 1), and all participants preferred the baseline visualisation (Image B, Fig. 9) over Image

A (7/7). Taken together, the findings delimit the workflow's current suitability for professional planting visualisation: in this GPT-4o-based configuration, the dominant limitations concern botanical and spatial validity (species identity, morphology, habit/layering, phenology, and geometric scale), rather than image-editing artefacts.

Image A (Fig. 4) and Figures 5-8 were generated with ChatGPT (Version GPT-4o) (OpenAI 2025). AI use was limited to workflow specification, prompt development, and image generation (Section 3.1).

Exploratory re-runs with newer model versions are planned, but require the same expert evaluation protocol before any performance claims.

Accordingly, the primary outlook is empirical and methodological:

1. re-run the same evaluation protocol across emerging multimodal image models to quantify whether botanical and spatial validity improves under identical constraints;
2. broaden testing beyond a single realised case by including multiple planting typologies and contexts to reduce the risk of over-generalisation
3. extend the workflow toward explicit seasonality control and time-based simulation once model/tool affordances allow such constraints to be expressed and checked reliably. Where possible, prompts, structured content profiles, and evaluation materials should be provided as supplementary resources to support reproducibility.
4. Future work should test the workflow in other design-visualisation contexts and benchmark the structured, JSON-guided prompting approach against ad-hoc prompting under controlled conditions to assess gains in transparency and repeatability.

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Enhancing Participatory Urban Design with AI-Generated Visualisations: A Case Study of Nelson, New Zealand

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Abstract: Cities around the world are grappling with the challenge of the loss of vitality as a consequence of economic and social changes. Participatory design is one approach for tackling this challenge, engaging the public in developing visions for revitalisation. Imagining potential futures can be difficult for non-designers, and techniques for visualisation are an important component of participatory design. Artificial Intelligence (AI) is emerging as a tool that can bridge between participants' views on revitalisation and the visualisation of possible futures. Through using a scenario-based approach, with scenarios informed by international revitalisation strategies, we developed visualisations of three options to be used in participant workshops. Two approaches were compared: introducing AI images before or during stakeholder engagement, highlighting trade-offs between efficiency and inclusivity. Findings indicate that AI visualisation enhances understanding, inclusivity, and ownership but may mislead if visuals are overly polished or contextually inaccurate. Overall, AI serves as a supportive tool, complementing human expertise, demonstrating potential in participatory urban planning while emphasising engagement and context-sensitive application.

Keywords: Participatory design, urban revitalisation, AI-generated images, scenario visualisation, Artificial Intelligence (AI)

1 Introduction

Urban revitalisation is becoming increasingly important as cities begin to shift away from car dependency. Large high-density cities like Copenhagen and New York have drawn attention for prioritising people over vehicles by reclaiming city spaces for pedestrians and designing environments that foster public life. This includes creating vibrant public spaces that support social interaction and placing human needs at the centre of urban design (GEHL 2010, GEHL & SVARRE 2013). This focus on people and human needs raises the question of how the public can become meaningfully involved in shaping a city's future.

Nelson, a small city in the South Island of New Zealand, with a culturally and architecturally rich historic centre, faces challenges to its urban vitality, including low permanent residency and large areas of surface parking (GRAY 2023). These local issues mirror broader national trends in New Zealand, such as car dependency and urban shrinkage, as tens of thousands of New Zealanders leave the country (DUFF 2025, ENVIRONMENTAL HEALTH INTELLIGENCE NEW ZEALAND 2024). Similar challenges are seen internationally, including Finland's shrinking small cities, where smart shrinkage strategies have been introduced (ALBRECHT & KORTELAINEN 2022) and North American strategies to counter suburbanisation Filion et al. (2004). In relation to car dependency, Gehl's (2010) people-first principles highlight the shift from car-centric to human-centred design.

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Applying international ideas about revitalisation in a local participatory design context brings two key challenges. The first is in adapting the strategies to the local context, and the second is in ensuring that they are understandable for the participants. These challenges point to a key question: How can visual tools like AI-generated images and scenario development respond to the local context and help stakeholders imagine and respond to these scenarios?

2 Participatory Design and Artificial Intelligence in Urban Development

The integration of Artificial Intelligence (AI) into participatory planning has the potential to contribute to the transformation of decision-making and urban design processes. One of the most visible applications of AI in urban design is the use of AI-generated images. These images have become increasingly common in the fields of engineering, architecture, construction and urban landscapes, particularly in generating 'detailed' and 'compelling' images. AI tools enable the automatic creation of realistic representations of buildings and urban landscapes from text descriptions, using structured processes in applied contexts (FALLACARA et al. 2023).

Recent studies have examined AI's role in participatory urban design, from stakeholder-created images (e. g. KIM et al. 2022, VON BRACKEL-SCHMIDT et al. 2024) to tools like UrbanistAI and PlacemakingAI for visualising street designs (e. g. VALENÇA et al. 2025). Some create images before engagement for stakeholder selection (KAVOURAS et al., 2025), others refine and enhance participant-taken photos through generative AI tool (PREUSSNER et al. 2025), and some apply AI to scenario-based planning, forecasting futures for cities after revitalisation and developing master plans (CAMARDA & PATANO 2024, SPANIOL & ROWLAND 2023). This research applies AI-supported participatory design in a super-diverse, small city in New Zealand, adapting global strategies to a local context. Unlike most studies that use AI interactively *during* workshops, our approach introduces AI-generated scenarios *beforehand*, enabling participants to combine text and visuals for more informed decisions.

3 Methods and Results

This section folds the research methods and results together, emphasising the methodological focus for this paper. Through focusing on the approaches of scenario development and the use of AI-generated images, we identify a range of key considerations for participatory design approaches.

3.1 Scenario Development

Scenario development is a valuable tool in urban planning and design, especially for envisioning potential futures for cities. According to Jonas (2001), a scenario itself can be considered a design, offering a cohesive and flexible framework for imagining different futures without strict adherence to an existing reality. Traditional scenario development approaches use maps or text, which can be difficult for non-professionals to understand. Hand sketching can be used to augment the map or text-based information, but this is time-consuming and requires specialist skills.

In this study, scenario development serves to explore potential futures for Nelson's city centre through participatory processes that integrate perspectives from design experts, non-design experts, residents, and visitors. To examine alternative approaches to urban revitalisation in Nelson's city centre, three distinct scenarios were developed, informed by international revitalisation strategies that address comparable challenges:

- Shrinkage Downtown Renewal – based on small Finnish city strategies, focusing on addressing shrinkage, integrating shopping malls, and fostering community engagement (ALBRECHT & KORTELAINEN 2022).
- Urban Well-being Oasis – derived from Jan Gehl's 12 quality criteria, emphasising pedestrian-friendly, socially vibrant spaces (GEHL 2010, 239).
- Economic and Infrastructural Revival – inspired by small American and Canadian city strategies, prioritising economic growth, infrastructure upgrades, markets, and downtown renewal (FILION et al. 2004).

3.2 Scenario Visualisation with AI-Generated Images

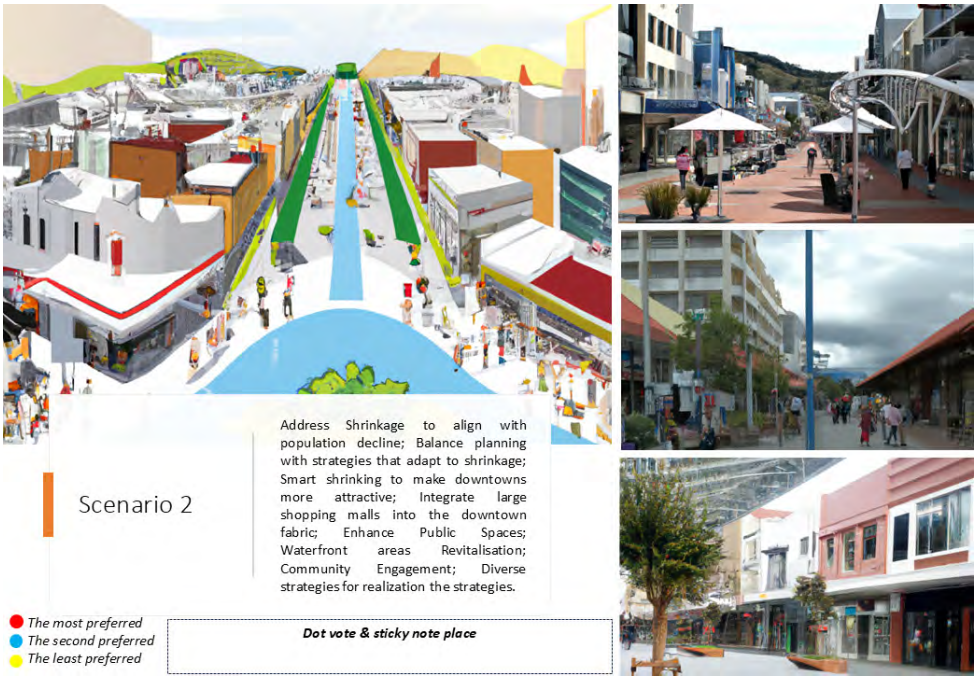

Fig. 1: One of the scenarios created for the pilot study (Authors); the images generated by DALL.E.2

Our research used visualisations to engage Nelson stakeholders in city centre revitalisation scenarios, making urban planning concepts more accessible and supporting preference communication. Several AI platforms were tested. Using a pilot study, we tested the scenarios and images that were generated from text by the DALL·E 2 (OPENAI 2023) platform (Fig. 1). Pilot study participants commented that the images were generic and lacking a specifically Nelson context.

Fig. 2: The top line shows the usual UrbanistAI application, where images are generated during workshops, contrasted with our approach on the bottom line, where we began by creating AI images (Authors)

Fig. 3: The Shrinkage Downtown Renewal Scenario. The scenario sheet was developed by the authors. All images were created in UrbanistAI.

After further investigation, UrbanistAI was selected as a more effective platform, providing contextually relevant images for urban revitalisation. The research team critically reviewed these images for their representation of local features, ensuring participants could focus on Nelson's future rather than filling gaps in generic visuals.

UrbanistAI (2025b) is a novel platform that generates customised urban design proposals, enhancing participatory planning through scenario exploration, addressing common challenges and aligning with communicative planning theory (LARSEN & LINDSTRÖM 2024). Users can specify parameters such as location, street layout, building types, and design preferences, which the algorithm translates into tailored urban visualisations. Unlike DALL·E's more generic, less context-specific images, UrbanistAI produces realistic visuals grounded

in local context, making it particularly valuable for this study by depicting Nelson's environment in detail and strengthening stakeholder understanding and engagement.

For this study, AI-generated images were prepared in advance, allowing participants to engage with each scenario through its criteria and corresponding visualisations of potential impacts in Nelson city centre. Unlike other UrbanistAI applications that generate live images during workshops, a pre-generation approach was adopted for four reasons: the scenarios had predefined goals; sessions needed to be short and focused; venues could not support large interactive workshops; and the project was managed by a small research team. This ensured engagement remained structured, feasible, and aligned with the study's objectives (Fig. 2).

Fig. 4: The Urban Well-being Oasis Scenario, based on Gehl's 12 quality criteria. The scenario sheet was developed by the authors. All images were created in UrbanistAI.

The AI-generated images were integrated into the scenarios based on the three international strategies. Each image was carefully critiqued by the research team for its generic versus locally specific qualities, as it was essential to avoid presenting participants with placeless imagery. Our intention was to ensure that participants could focus on imagining the future of Nelson rather than mentally compensating for generic visual content. Feedback from the pilot study reinforced this need: participants reported difficulty relating the initial images to Nelson and requested additional contextual information to better understand each scenario. In response, we revised the materials by adding each scenario's title, key focus criteria, and the new set of AI images generated by UrbanistAI, resulting in a clearer understanding, deeper involvement, and more effective engagement during the workshops and interviews (Figs. 3, 4 & 5).

Fig. 5: The Economic and Infrastructural Revival Scenario. The scenario sheet by the authors. All images created in UrbanistAI, except the bottom left from DALL·E 2.

3.3 Recruitment of Participants and Data Analysis

A participatory approach and dot voting were used to identify community priorities, allowing participants to rank scenarios using coloured dots (DALTON 2019). Following DiGiovanni et al. (2023), dot surveys and sticky notes helped visualise preferences and support engagement. To reduce the influence of early visible votes, participants cast their votes independently before discussing their choices in the group.

Participants were grouped as design experts, non-design experts, and others (residents and visitors). Following the necessary Human Ethics protocols, recruitment began with email outreach and was strengthened through attendance at the City Revitalisation Summit (SHAPE NELSON 2024). Ethnographic and snowball sampling during three months of fieldwork further expanded participation, resulting in a total of 22 participants, three design experts, five non-design experts, and 14 others, across workshops and interviews. They are all referred to by pseudonyms to maintain their anonymity.

Data analysis combined dot voting to quantify scenario preferences with qualitative examination of sticky notes to understand participants' reasoning. Votes were colour-coded (the most preferred (red), second preferred (blue), and least preferred (yellow) ideas among design **experts (DE)** (dark purple), **non-design experts (NDE)** (light purple) and **others (O)**(grey)) and organised in Excel, and the results are presented in charts showing key trends.

3.4 Results

The results of this study show that design experts were generally more in favour of the Economic and Infrastructural Revival Scenario, whereas participants in the others group preferred the Shrinkage Downtown Renewal Scenario. The Urban Well-being Oasis Scenario was typically a second preference for design experts, least preferred by others, and showed mixed – both highest and lowest – preferences among non-design experts (Fig. 6). Importantly, these preferences reflect participants' perceptions of each scenario as an integrated whole, rather than a response to the images alone – although the AI-generated images formed part of the overall scenario package they evaluated.

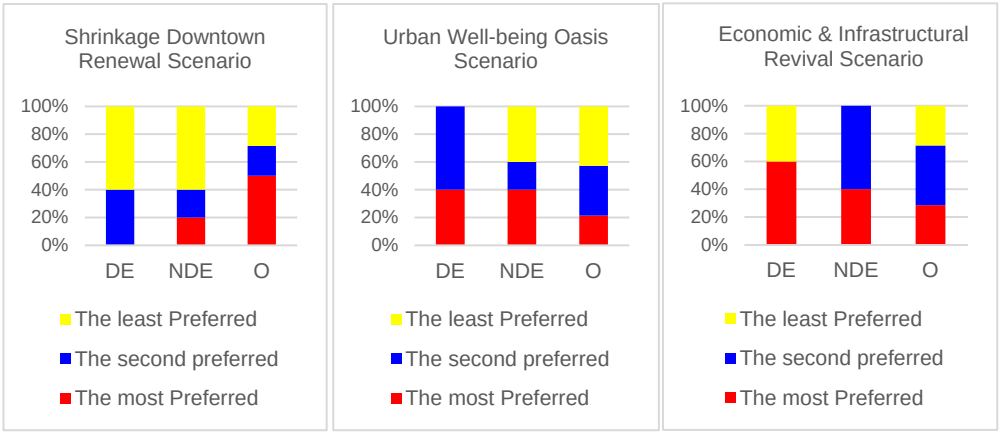

Fig. 6: Scenarios' preferences by design experts (DE), non-design experts (NDE) and others (O) (Authors)

The objective of the research project was not to test the images, but to use the images in support of participants' understanding of the scenarios. Participants' feedback on the scenarios show that the AI-generated images supported each scenario in both positive and negative ways.

Shrinkage Downtown Renewal Scenario

Reactions to the Shrinkage Downtown Scenario showed that participants were influenced by the AI-generated waterfront imagery, which connected Trafalgar Street directly to the beach. Although waterfront revitalisation was referenced in the criteria, many comments specifically highlighted the idea of linking Nelson to the sea, suggesting that the images strengthened this association. As Jordan (DE) said, *"We need to connect the city to the beach … I like green spaces and waterfront scenario in this scheme."* Similarly, Ella (NDE) emphasised that the *"linkage for Nelson mountains to sea is important."* Emma (O) expanded on this, appreciating that *"the Maitai [River] connects the city to the waterfront."*

Interestingly, some reactions were directed at landscape elements – such as parks and walkways – that were not explicitly included in the written criteria but appeared in the visuals. Lucas (O), for instance, explained that parks and walkways *"spread people out more,"* conflicting with his vision of a lively, densely populated city centre. This shows how AI images

can introduce design implications that participants respond to even when they are not part of the formal scenario structure.

Urban Well-Being Oasis Scenario

Participants' engagement with the Urban Well-Being Oasis Scenario reflected the supporting role of AI images, though with mixed perceptions of the feasibility of the scenario. Eva (O) expressed the scenario as *"Visually pleasing"* and Alex (DE) acknowledged improvements in the *"look and feel"* of the scenario but pointed out that it *"does not address the economic drivers."* This indicates a gap between the aesthetic emphasis of the scenario and participants' broader priorities.

This scenario again highlighted how the AI-generated images provoked responses to aspects that were peripheral to the principles. Street furniture, for example, was only a subtle element in the criteria but prominent in the images. Sophie (NDE) cautioned that *"street furniture is expensive and easy to get wrong."* This exemplifies how the AI-generated visualisations provide scope for capturing unanticipated commentary on the scenarios.

Overall, the images contributed to a perception of the scenario as welcoming, sociable, and visually pleasant. Lucas (O) envisioned *"Love the many locations suited to socialising in a composition setting. Would be suited to cool cafes and bars of different types with their settings overflowing into the street scene"*. He also appreciated designing new community spaces around Nelson's old trees that was only evident in the images not the written criteria of the scenario. However, not all reactions were positive: Mia (O) considered the scenario *"too idealistic,"* while Grace (O) felt it was *"a bit too modern"* and lacking in greenery.

Economic & Infrastructural Revival Scenario

Reactions to the Economic & Infrastructural Revival Scenario showed how the AI images contributed layers of interpretation beyond the written criteria. Although the scenario did not emphasise modernity, Lucas (O) perceived the scenario as *"a combination of cultural/ historical with some modern spaces"* which aligned with his preferred vision of city centres. At the same time, the presence of vehicles and road infrastructure in the images shaped his response negatively, as he noted the *"Looks to have a large vehicle/ road presence which I am not a fan of"*.

Some participants saw potential for a vibrant and economically active city centre, with Ella (NDE) expressing enthusiasm for *"the vibrant feel [of] markets."* Others, however, reacted to what they perceived as a lack of child-friendliness, an interpretation likely driven by what the scenario and its images did not show. Mia (O) suggested the need for a *"youth centre for kids,"* and Layla (O) placed this scenario last because it did not serve her needs as a mother of young children. Visual greenery also shaped reactions: Grace felt the scenario *"fits best"* for her but would benefit from *"a bit more green."*

Overall, participants frequently responded to a combination of scenario narratives and the AI-generated images, with the visuals often amplifying, reframing, or even overshadowing the written criteria. The elements mentioned above for the scenarios were interpreted through what participants could see in the images or what they perceive from the scenario in general without referring to those elements directly, highlighting the powerful role of visualisation in shaping scenario evaluation.

4 Discussion

This study contributes to the Digital Landscape Architecture (DLA) community by demonstrating how AI visualisation can enhance participatory scenario planning for urban and landscape contexts, supporting participants' understanding of complex scenarios. By combining textual scenario descriptions with visualisations, diverse stakeholders – including designers, non-designers and participants from different cultural backgrounds – could engage meaningfully. The findings highlight both positive and negative outcomes of using AI visualisation and illustrate two distinct approaches, pre-created versus co-created images, which are discussed in the following sections on positive outcomes, challenges, and different approaches.

4.1 Positive Outcomes of Using AI for Visualisation of Scenarios

AI-generated images provided participants with tangible representations of potential futures for Nelson, enhancing engagement and making abstract ideas more concrete. When combined with the scenario text, the visuals helped participants interpret spatial, social, and cultural aspects more effectively – for example, a Māori (indigenous New Zealander) participant noted that the Urban Well-being Oasis Scenario reflected Māori culture. AI also enabled non-designers to express and engage with ideas quickly, supporting Çay et al. (2020), who note that AI helps those who find sketching challenging. Although selecting a suitable platform took time, once identified, AI allowed for faster and more context-sensitive visualisation than manual sketching.

The images also encouraged reflection on elements not explicitly included in the written criteria, such as family-friendly spaces, community areas around trees, and connections to water. By providing a shared visual reference, they made possible futures easier to understand for participants with diverse expertise and cultural backgrounds. This combination of text and visualisation deepened involvement, enriched discussion, and strengthened shared understanding and ownership, the key goals of participatory planning. These findings align with Andrews et al. (2022, 34), who emphasise the growing importance of AI in planning and the need for planners to understand how AI shapes practice now and in the future.

4.2 Challenges of Using AI-Generated Images

While AI-generated images increase accessibility, they can unintentionally mislead. As Baird and Rennie (2017) note, advanced visualisation technologies can create a false sense of accuracy, with unintended visual details leading participants to assume certain elements are fixed parts of a proposal. This underscores the need for careful curation, transparency, and visual literacy so participants can critically engage with what they see rather than accepting images at face value.

In some of our workshops, participants sometimes reacted to distracting details of the images rather than the scenario itself. For example, Grace (O) described the Urban Well-being Oasis Scenario as *"too modern for Nelson,"* and Lucas (O) noted that *"parks and walkways like in this option [Shrinkage Downtown Renewal Scenario] spread people out more,"* conflicting with his preference for a vibrant city centre. We believe their reactions were shaped more by the distracting details in the AI-generated images, as 'modernity' or 'parks and walkways' were not described in the scenarios' texts. Such details may not have appeared in a simple sketch or text-based scenario, illustrating how polished visuals can shape interpretation.

Challenges were also evident in generating AI images with DALL·E-2, which struggled to produce contextually realistic visuals for Nelson, making the process time-consuming. This suggests that relying too heavily on AI tools can be inefficient and may not fully replace traditional methods like sketching. Therefore, while AI has significant potential in urban planning, it does not share designers' deep understanding of context or design intent. As Li (2024) noted, designers' roles cannot be fully replaced by AI. The findings of this study also support this point, showing that AI-generated images can be misleading by introducing visual elements that were not intended to be part of the scenario.

4.3 Different Approaches of Using AI and Scenario Development in Participatory Designs

The stages of participatory workshops are not fixed; they can overlap or shift depending on the study's objectives and the integration of AI-generated images. If AI-generated images are made before the workshop, as in this study, the order of the other stages changes, affecting how scenarios are developed and how participants engage. If the images are introduced during the workshop, as in UrbanistAI (2025a) approach, participants can give feedback and make changes in real time (e. g. KIM et al. 2022, VON BRACKEL-SCHMIDT et al. 2024), and the scenarios are refined afterwards. This flexibility shows how participatory design can adapt to different study goals. The timing of AI use – before or during the workshop – shapes the workshop's structure and leads to two different approaches:

Approach One: AI and Scenario Development First, Then Stakeholder Engagement

Urban revitalisation begins with identifying a core problem. In this approach, early project development is prioritised through AI-generated images, which accelerate visualisation and replace time-intensive sketching. Stakeholders are then selected to ensure diverse perspectives, followed by participatory methods such as workshops or interviews. Here, AI serves as the central tool for shaping and refining scenarios, which participants later evaluate through techniques like dot voting (Fig. 7).

Fig. 7: Pathways of Participation in Urban Revitalisation- Approach One (Authors)

Approach Two: Stakeholder Engagement First, Then AI and Scenario Development

Alternatively, stakeholder selection is made earlier in the process, ensuring that experts, non-experts, and community members shape the discussion before defining project strategies. In this sequence, methods such as workshops or interviews are chosen earlier to guide the conversation, and only then are AI-generated images and digital tools introduced to visualise and refine urban scenarios (Fig. 8).

Fig. 8: Pathways of Participation in Urban Revitalisation- Approach Two (Authors)

While both approaches integrate interactive techniques like scenario development and AI-generated images, their focuses differ: one prioritises early project development and visualisation, while the other leans toward stakeholder-driven discussions before scenario creation.

The Advantages and Disadvantages of the Two Approaches

These two approaches to the urban revitalisation participatory design process differ in how and when stakeholders are involved, influencing both the efficiency and inclusivity of the project. In the first approach, AI-generated images and digital tools are used early to visualise potential transformations, providing a clear direction and focused discussions on pre-developed scenarios. This enhances efficiency by replacing time-consuming image generation and offering immediate visual guidance. However, stakeholders are introduced later, limiting their influence to refining rather than shaping ideas, which may embed designer biases. Nonetheless, negotiation can allow participants to contribute to the creation of new perspectives.

The second approach engages stakeholders before scenario development, ensuring diverse voices shape the process from the outset. This promotes an inclusive, adaptive framework, fostering ownership and collaborative problem definition that better reflects community needs. However, this inclusivity can slow down the process, as discussions often start without concrete visualisations, making it harder to develop shared understandings and structured proposals and scenarios (VON BRACKEL-SCHMIDT et al. 2024). Without AI-generated images guiding early conversations, stakeholders may struggle to articulate their ideas clearly. This leads to prolonged deliberation before reaching actionable conclusions and increasing the risk of discussions drifting off-topic.

Ultimately, the effectiveness of each approach depends on the project's priorities. If efficiency and structured discussions are the main goals, beginning with scenario development and AI visualisation ensures a streamlined workflow. However, if inclusivity and community-driven decision-making are paramount, engaging stakeholders early allows for richer, more representative outcomes.

5 Conclusion and Outlook

This research demonstrates that the timing and positioning of AI integration within participatory processes significantly shapes engagement outcomes. AI-generated images can make scenarios more understanding, inclusive, and efficient, but they also introduce risks, as overly polished or misleading visuals may shape perceptions in unintended ways. The study compared two main approaches – using AI before conducting workshops or integrating it throughout the process – and showed that each has distinct advantages depending on project priorities. If efficiency and structured discussion are the goals, beginning with project development and AI visualisation ensures a streamlined workflow. Conversely, if inclusivity and community-driven decision-making are paramount, engaging stakeholders early allows for richer and more representative outcomes. In Nelson, pre-generated AI visuals proved especially effective in a small-city context with limited time, space, and resources, helping to keep engagement feasible and focused. Ultimately, AI should be seen as a flexible, supportive tool rather than a replacement for human expertise, with future applications requiring transparency and careful adaptation to local culture, context, and community needs.

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[AI as Collaborator] Integrating Machine Learning and Interactive Prototyping for Adaptive Public Space Design

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Abstract: Artificial intelligence in landscape architecture is often limited to text-to-image tools, offering minimal design control and limited rigor. This study proposes a hybrid digital-physical framework in which machine learning supports spatial decision-making while maintaining human oversight. A convolutional neural network (CNN), trained on spatial configuration data, predicts optimal gathering areas based on environmental factors such as temperature, sunlight, and tree placement. Using Grange Park as a case study, the model achieved 87.5% classification accuracy. Integrated with an Arduino-driven physical prototype, the system demonstrates how predictive modelling and tangible interaction can enable more adaptive, evidence-based urban public-space design.

Keywords: Machine learning, CNN, interactive prototyping, adaptive design, public space

1 Introduction

Designing responsive and inclusive public spaces remains a critical challenge in landscape architecture. Traditional design methodologies are valuable, but they rely on static analyses and heuristic knowledge, which can be unsuitable to the dynamic nature of urban environments. Climate change, seasonal variations, and evolving human activities require designs that adapt in real-time to shifting conditions. Recent advances in artificial intelligence (AI) and machine learning (ML) offer the potential to enhance the adaptability of public space design by drawing insights from large datasets and providing predictive models for spatial configurations. Furthermore, interactive technologies enable designers and stakeholders to engage directly with design outputs, facilitating iterative testing and refinement.

This study proposes a new hybrid workflow that combines machine learning-based spatial predictions with tangible prototyping. By integrating a convolutional neural network (CNN) with an Arduino-driven physical model, the framework allows designers to test, visualize, and refine design hypotheses in real-time. The primary objective is to create a system capable of learning from environmental and human behavioral data, such as temperature, sunlight, and pedestrian circulation and translating this knowledge into spatial recommendations for public space. Grange Park was selected as the case study due to its spatial diversity, high level of social activity, and suitability for testing adaptive, data-driven public space design. Its varied combination of trees, open areas, and circulation paths provides a clear context for examining how environmental and spatial factors influence gathering behavior. The park's manageable scale and legible layout align well with the grid-based analytical and physical modeling approach, allowing essential urban relationships to be studied without oversimplifying real-world conditions.

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By leveraging AI as a collaborative tool in the design process, this research seeks to shift the role of technology from a tool for automation to a partner in the creative process. This paper examines how this emerging approach, integrating computational predictions with physical models, can be implemented within a small-scale design process, and whether it has the potential to enhance both the efficiency and inclusivity of urban space design, ensuring that public spaces are not only functional but also adaptable to future needs.

2 Background and Related Work

Computational and data-driven methods are increasingly central to landscape and urban design. Machine learning techniques, particularly convolutional neural networks (CNNs), have been widely adopted in environmental analysis, spatial classification, and design optimization (SHAO et al. 2025). CNNs are a class of deep learning models specifically designed to process grid-like data, such as images or spatial data, by automatically learning spatial hierarchies of features. The power of CNNs lies in their ability to extract complex patterns from raw data, which can then be used for predictions or classifications. In the context of landscape architecture, CNNs can analyze environmental factors and spatial configurations, enabling the generation of optimized design solutions.

Studies such as DeepStreet (FANG et al. 2020) illustrate CNNs' ability to generate street-network layouts aligned with contextual logic, while pedestrian-flow simulations (JIANG et al. 2024) show how neural network-based models can capture complex movement dynamics. However, most existing work remains digital and detached from physical prototyping.

Xun Liu's The Third Simulation presents a seminal digital-physical framework in which tangible landscape models are continuously coupled with real-time computational simulations through augmented reality, forming a recursive feedback loop between material manipulation and numerical analysis (LIU 2020). In Liu's work, physical models are sensed using cameras and depth scanners, while computationally intensive hydraulic simulations run in the background to visualize dynamic environmental processes such as flow, sedimentation, and erosion.

Building on this conceptual foundation, this research adopts the principle of digital-physical feedback but diverges methodologically by replacing physics-based simulation with a lightweight convolutional neural network trained on designer-generated spatial logic. A lightweight CNN was chosen to enable real-time prediction, minimize hardware and computational requirements, and support iterative interaction with the physical prototype during the design process. Rather than simulating environmental processes directly, the CNN produces real-time spatial suitability predictions that are materialized through a physical prototype, prioritizing speed, accessibility, and iterative designer interaction while maintaining a human-in-the-loop design workflow. Parallel developments in interactive physical modelling demonstrate how tangible systems can enhance understanding and collaboration. Fukuda et al. (2016) developed a motorized physical model linked to Building Information Modelling (BIM) data for rapid visualization, while Kanis et al. (2013) used sensor-equipped scale models to simulate public-square dynamics, improving public engagement. Despite these advancements, few projects integrate machine-learning outputs directly into physical prototypes, leaving a gap between predictive analytics and experiential evaluation. This research addresses that gap by developing a fully connected CNN-Arduino pipeline that allows spatial predictions to manifest physically and be iteratively refined.

3 Methodology

The research employed a multi-stage process: Data Collection and Dataset Design, Data Preparation and Encoding, Machine Learning Model, and Physical System Integration (Fig. 1).

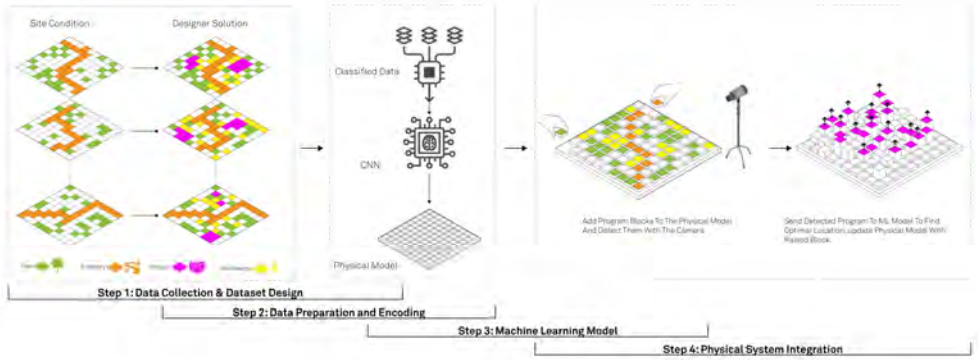

Fig. 1: Process diagram illustrating the research method from data collection to physical integration

3.1 Data Collection and Dataset Design [Step 1]

Grange Park, adjacent to the Art Gallery of Ontario, was selected as the study site. A 16 × 16 meter study area was divided into sixteen 4 × 4 meter cells. The research team take the role of a designer in the design process. The research team provided multiple plan variations for the study area; each variation was intentionally composed with respect to five key variables: (1) temperature (microclimatic comfort), (2) sunlight exposure (daily direct-light hours), (3) pathway connectivity (spatial accessibility), (4) tree presence (shade and spatial structure), and (5) human activity density (anticipated occupancy patterns).

Each variation was exported as a plan-view image and analyzed using OpenCV, an open-source computer-vision library that detects shapes, colors, and spatial features. The program segmented each image into cells and translated the visual information into numerical matrices representing the five variables. These matrices formed the dataset for the CNN, which linked spatial and environmental conditions to predicted gathering intensity. The same 4 × 4 grid structure was implemented physically, with each cell connected to a servo motor that adjusted height based on the CNN's predictions.

3.2 Data Preparation and Encoding [Step 2]

The research team randomly placed different program elements such as: people, people-with-tree, tree, and pathway across a 4 × 4 square site. In total, 120 variations were created. For each variation, the designer identified the best possible location for a gathering space. The data from these site layouts were then encoded into a simple grid format in which each cell represented a type of activity or element. Logical spatial rules were included to keep

the designs realistic, such as keeping pathways short and grouping cells that represented social activities in close proximity.

3.3 Machine Learning Model [Step 3]

A lightweight CNN was developed to learn spatial relationships between environmental conditions and designer-identified gathering spaces. The CNN was implemented using Python and the Keras deep learning framework, a high-level neural network API for rapid model development, with TensorFlow serving as the computational backend for efficient numerical optimization. The model was trained using a supervised learning approach, where the input consisted of 120 encoded 4 × 4 grid variations, each representing different spatial and environmental configurations.

Each site layout was represented as a one-hot encoded 4 × 4 grid, with each cell encoding a programmatic condition (e. g., human activity, trees, pathways) derived from the OpenCV-based image processing described in Step 2. This encoding allowed the CNN to focus on spatial adjacency and pattern logic rather than raw visual data. The training dataset varied in terms of layout configurations, with different combinations of programmatic elements placed across the grid. These variations were manually designed by the designer/research team to reflect realistic urban conditions while adhering to logical spatial rules, ensuring a broad range of possible scenarios.

The machine-learning model was designed to read the grid in a way similar to how a designer interprets a plan. It looks at small groups of neighboring cells to understand how elements are arranged and how they relate to one another, learning patterns such as proximity, clustering, and alignment. Based on these relationships, the model assigns a likelihood to each cell, indicating how suitable that location is for a gathering space. The result is a spatial map that reflects the designer's underlying logic while presenting it as flexible suggestions rather than fixed outcomes.

During training, the model adjusted itself to reduce prediction errors using a standard optimization method. To avoid learning patterns that only apply to the training examples, the training process was stopped automatically when performance on a separate validation set no longer improved. Model performance was evaluated using classification accuracy, which represents the percentage of grid cells for which the model correctly identified whether they were gathering locations.

In addition to the CNN predictions, a set of rule-based post-processing steps was applied to ensure the results followed basic spatial design logic. First, cells identified as circulation corridors (blue cells) were explicitly masked so they could never be classified as gathering spaces, regardless of the model's confidence. This reflects the design assumption that people do not gather within active walkways. Second, a simple bridging rule was introduced to improve spatial continuity: if a cell was predicted as non-gathering but was positioned between two adjacent gathering cells either vertically or horizontally, it was reclassified as a gathering cell, provided it was not part of a circulation zone. This operation helped reinforce clustered and connected gathering areas rather than isolated points. Together, these rules ensured that the final output combined learned spatial patterns from the model with explicit designer-defined constraints, producing results that were both computationally informed and spatially coherent.

3.4 Physical System Integration [Step 4]

The trained convolutional neural network was integrated into a tangible physical prototype controlled by an Arduino microcontroller, forming a bidirectional digital-physical feedback system. Rather than functioning solely as a visualization device, the prototype was designed as an interactive interface that allows designers and participants to actively manipulate spatial inputs and immediately observe computational responses.

The physical model consists of a 4 × 4 grid, corresponding directly to the digital data structure used in model training. Users interact with the system by placing small wooden square markers – each encoded with a specific color, onto individual cells of the grid. These markers represent different spatial and programmatic conditions:

Purple: Human presence and activity indicators; **Green**: Tree canopy; **Orange**: Co-presence of human activity and trees; **Blue**: Walkways and circulation corridors**; White**: Neutral, unclassified, or unconstrained space.

The "people-with-tree" category was added to represent environments where human activity and tree canopy overlap. This category helps capture conditions related to comfort, microclimate, and social preferences that can't be fully understood by looking at people or trees separately. It allows the model to better assess how environmental and social factors impact the suitability of gathering spaces.

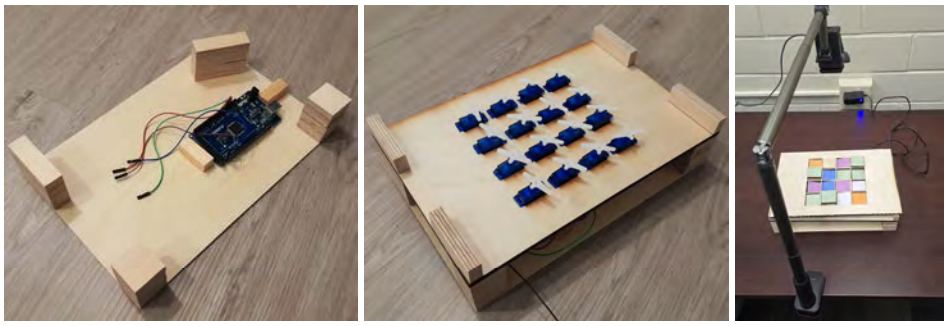

Fig. 2: Physical system components – Left: Arduino microcontroller, Center: Servo motors for grid actuation, right: Webcam used to capture the physical model and provide input to the machine learning

An overhead webcam continuously captures the physical configuration of the grid (Fig. 2). Using computer-vision techniques, the system detects the colour and location of each marker, translates this visual information into numerical values, and reconstructs the corresponding input matrix. This matrix is then passed to the trained CNN, which evaluates the spatial arrangement and predicts optimal locations for gathering spaces.

The model's predictions are transmitted back to the physical prototype through a serial connection, triggering servo motors to raise or lower individual grid cells (Fig. 3). In this way, the physical surface dynamically responds to user input, machine learning inference, and tangible spatial representation. This interaction transforms the prototype into a collaborative sandbox, enabling iterative exploration, rapid testing of design hypotheses, and shared discussion among designers and stakeholders.

By embedding sensing, computation, and actuation into a continuous loop, the system supports a designer-in-the-loop workflow in which digital intelligence augments, rather than replaces, human spatial reasoning.

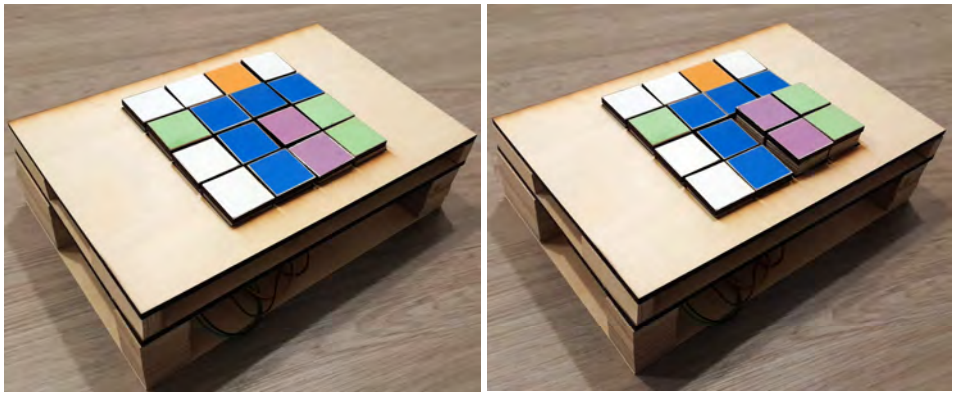

Fig. 3: Physical system integration and machine learning feedback – Left: 4 × 4 grid with colored spatial inputs, Right: Raised cells indicating optimal gathering spaces predicted by the model

4 Results and Analysis

An accuracy of 87.5% was achieved by the model in predicting gathering spaces. To calculate this, the likelihood of each cell being a gathering space was predicted by the model. A threshold of 0.45 was then used to classify each cell as either a gathering space or not; this value was selected empirically through iterative testing on the validation set, as it provided the best balance between correctly identifying gathering spaces and avoiding false positives, particularly in ambiguous edge cells. This slightly lower-than-default threshold allowed the model to capture spatial clusters more effectively. A post-processing step was then applied to exclude areas where gathering spaces were not allowed, such as walkways, ensuring that the final predictions remained consistent with the design rules and spatial constraints.

The model's performance was evaluated by comparing its predictions to the actual design. The number of correctly predicted cells was counted, and the ratio of correct predictions to total cells was calculated, resulting in an accuracy rate of 87.5%. This indicates that the model correctly predicted gathering spaces most of the time.

When the model's predictions were compared to those made by human designers, substantial overlap was observed in the main gathering areas. Shaded or visually balanced locations were preferred by human designers, while spatial connections and proximity to pathways were emphasized by the model. This shows how the model's calculations and human intuition can complement each other in designing public spaces.

The physical prototype, controlled by an Arduino, transformed the model's predictions into a 3D form. Cells predicted as gathering spaces were raised, creating an interactive and dy-

namic display. Minor issues with motor alignment and color detection under different lighting conditions were observed, but efforts are ongoing to refine the system for better performance and smoother integration between the digital model and the physical prototype.

5 Discussion

The study investigates a designer-in-the-loop workflow and situates AI neither as the primary decision-maker nor as a simple tool, but as a collaborator. Machine learning can capture and generalize spatial design logic from structured datasets provided by designers, and integrating these predictions into interactive prototypes enhances both understanding and engagement. The tangible model served as a communication medium between computational systems and human designers, encouraging dialogue around how design decisions emerge from data.

These findings support prior research emphasizing the role of computational design in facilitating adaptive and participatory processes (Xing et al. 2024, Carta 2022). Unlike previous digital-only frameworks, this work's digital-physical integration enabled direct manipulation and observation of spatial outcomes, transforming abstract predictions into experiential forms.

Although projection-based systems could deliver faster and higher-resolution visual updates, the objective of this research was not to maximize graphical immediacy but to establish an embodied, interactive feedback loop between physical manipulation, machine-learning inference, and spatial response. In this context, "real-time" refers to computational responsiveness within an iterative design cycle rather than purely instantaneous display speed. The servo-driven physical actuation was intentionally adopted to translate predictive outputs into tangible, volumetric change, supporting spatial legibility and reflective engagement. By prioritizing material interaction over screen-based representation, the system positions AI as a collaborative design mediator rather than a passive visualization tool.

5.1 Grid-Based Physical Representation

The project employs a simplified 4 × 4 pixelated grid aligned with sixteen servo motors to clarify spatial and programmatic relationships rather than replicate continuous landforms. This discrete structure balances mechanical feasibility and spatial expressiveness, enabling controlled real-time actuation while isolating key spatial variables such as proximity and adjacency to examine the emergence of gathering spaces. Raised and lowered cells serve as legible indicators of relative spatial suitability, emphasizing decision-making logics over formal realism. Although higher-resolution or continuous systems could enhance representational fidelity, they may obscure the explicit spatial relationships central to the study. Limitations include a rule-based, designer-generated training dataset with limited contextual diversity, a relatively small sample size that constrained the neural network's generalization capacity, reduced spatial resolution inherent in the 4 × 4 grid, and minor mechanical inconsistencies in the prototype, all of which suggest directions for future refinement in dataset expansion, resolution enhancement, and system robustness.

5.2 Data Manipulation model (ML & CNN vs Multi-agent & Agentic AI)

A comparison with multi-agent systems (MAS) and emerging agentic AI frameworks clarifies the methodological positioning of this study. MAS simulate spatial outcomes through bottom-up behavioral interactions over time, and agentic AI systems extend this logic toward greater autonomy and goal-directed decision-making. Such approaches are well suited to modeling dynamic crowd behavior and long-term adaptation. However, the objective of this research was not to simulate temporal or autonomous behavior, but to infer spatial suitability from structured, designer-defined environmental relationships within a grid framework. A lightweight CNN was therefore selected for its capacity to efficiently capture spatial adjacency and clustering while enabling deterministic, real-time predictions compatible with the physical prototype. This configuration preserves a human-in-the-loop workflow, positioning AI as a collaborator that generalizes design logic rather than acting as an autonomous agent.

6 Conclusion

The integration of a simple predictive model with a physical prototype demonstrates how computational methods and real-time results can work together to enhance understanding of spatial relationships and support participatory design. The findings suggest that this approach can be a useful tool for both research and design education by making digital predictions visible and interactive. However, this study does not claim that AI provides better solutions than human design judgement; rather, it shows how computational processes can complement, rather than replace, human creativity and reasoning, as well as serving as a collaborator.

6.1 Advantages (Pros)

This approach enables real-time visualization and rapid testing of spatial ideas while encouraging collaboration between digital modeling and hands-on, physical design. It also helps communicate design logic clearly to both experts and non-experts, making concepts easier to understand across different audiences. Additionally, it offers a low-cost, educational way to experiment with adaptive design ideas, supporting exploration and learning without requiring extensive resources.

6.2 Limitations (Cons)

Several limitations should be acknowledged. The dataset used in this study was designer-generated rather than derived from real-world observations, which limits the diversity and realism of the training examples. In future work, this limitation will be addressed by incorporating empirically grounded data, such as observational studies, sensor-based measurements, and user-behavior mapping, to supplement and validate the designer-authored dataset. As with most convolutional neural networks, the model's performance depends heavily on the quality and quantity of training data, and larger, more varied datasets are generally required to achieve stronger generalization. The training and optimization process will therefore continue to involve human verification, both in curating mixed empirical and designer-generated data and in evaluating model outputs, to ensure that predictions remain meaningful and aligned with design intent. The physical prototype also requires technical maintenance and coding expertise, which may limit accessibility for some designers. Finally, the small

4 × 4 grid simplifies real-world spatial complexity and cannot fully capture the nuanced environmental and social conditions present in actual public spaces.

Overall, this framework explores how data-driven methods and human decision-making can intersect in landscape architecture. Future work will involve clearly defined user groups, including professional landscape architects, design students, and selected public participants engaged through structured workshops. Designers and students will interact with the system during iterative testing sessions, and their feedback on spatial suitability, usability, and interpretability of predictions will be systematically collected and used to refine the training dataset, post-processing rules, and model parameters. Feedback from public participants will be gathered through observation and discussion to assess how computational predictions align with intuitive spatial understanding. By expanding the dataset, refining mechanical precision, and incorporating user feedback into model verification and optimization, the project contributes to a more data-driven and adaptive approach to urban-space design.

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Prompting Design: Evaluating the Impact of AI on Design Outcomes

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Abstract: This paper assesses how the integration of generative AI (GenAI) image tools impact landscape design processes and outcomes compared to traditional design methods with the goal of providing insight into GenAI's role as a design tool, its strengths and limitations, and its effectiveness in early-stage landscape architecture workflows. It describes a within-subjects crossover study of undergraduate landscape architecture students where they completed equivalent design tasks in two treatment groups utilizing either traditional design methods or GenAI-integrated design methods, self-reported their experience, and then assessed the quality of their designs using third party experts. The findings suggest that GenAI can help designers develop novel design concepts, and that it does not significantly alter quality of design outcomes when the designer is significantly in-the-loop with the GenAI workflow. Participants also generally reported positively on the impact of GenAI use on creative process. However, highest rates of GenAI use were correlated with lower evaluations, suggesting outcomes are improved by design maturity and GenAI use rather than GenAI as a blunt tool. The work contributes to a growing discussion on how AI can be integrated into design education and professional practice and helps elucidate previous findings on GenAI's value as both a creative and technical tool.

Keywords: Artificial intelligence, generative AI, design process, aesthetics

1 Introduction and Literature Review

Artificial intelligence (AI) is a broad term used to describe computer-based systems designed to perform complex tasks that normally would require human intelligence. AI systems are now widely used across various industries, including the architecture, engineering, and construction (AEC) professions (CHAILLOU 2021), where they assist with tasks such as data analysis, decision-making, and problem-solving. AI applications in landscape architecture are wide ranging, whether for predictive analytics, ecological modeling, landscape policy evaluation, or conceptual design generation, among other things (FERNBERG & CHAMBERLAIN 2023). Recently, image creation using generative AI (GenAI) models has become increasingly integrated into design workflows, automating certain tasks and providing new ways to generate and evaluate design concepts (REKKITKE & HAYLES 2025).

In landscape architecture, designers rely on logical and creative decision-making, balancing site constraints, programmatic needs, and aesthetic principles to create a harmonious design (NIJHUIS & VRIES 2019). While GenAI has shown potential as a design tool, it remains limited in its ability to fully replicate the complexity of human-led design, especially in its inability to contextualize design within the site (PLOENNIGS & BERGER 2023). Moreover, few design studies focus on AI's impact on design outcomes and AI's influence on designers' workflows, efficiency, and design decisions (AS et al. 2018, CHEN et al. 2023).

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2 Methods

This study employed a within-subjects crossover design to evaluate the impact of integrating GenAI into early-process workflows on design processes and outcomes. Participants (n=35, 18 male, 17 female) in the study were 3rd year undergraduate landscape architecture students who were assigned to one of two treatment groups utilizing either traditional design methods or GenAI-integrated design methods. In the traditional process students explored and developed design forms by hand and were allowed to use industry-standard digital tools (e. g. Adobe Creative Suite, CAD, etc.) to explore and refine a design schematic. This process mirrored traditional design processes used in the contemporary practice and instruction of landscape architecture. In the GenAI-integrated design process, students utilized the same traditional design approach, but their efforts were supplemented through using the GenAI program Midjourney to develop AI-generated images to inform their design concepts, primarily at the beginning of the design process when forms and element placement is most malleable. Each participant had creative control over how to incorporate GenAI into their process, whether abstracting, manipulating, or directly integrating the image outputs into their final work (Fig. 1). Participants were encouraged to utilize the generated imagery as inspiration to inform their design decisions, and not as a replacement for final outcomes – in other words, a "human-in-the-loop" process where human involvement in design decisions and production remains the main driver of the design outputs.

The participants completed a residential design project before switching between treatment groups to complete a second residential design project. The second project utilized the same lot and home size, with similar location on the lot, however the configuration of the interior and exterior of the house was altered to deter students duplicating design across rounds. The completed student designs (n=70) were evaluated by licensed landscape architects (n=3) utilizing a rubric composed of proven metrics for evaluating creative works from prior studies evaluating design outputs (HAN et al. 2021, CASAKIN & KREITLER 2006, DEMIRKAN & AFACAN 2012). The evaluators used a 5-point Likert scale in the rubric for each metric. The evaluators received both verbal and written instruction regarding each metric in the rubric prior to starting their evaluation (see Table 1 for a short description of each metric). To measure inter-rater reliability, the interclass correlation coefficient was calculated with good results, ICC (2,3) = .81, 95% CI [.72-.89], F (69, 138) = 6.88, p <.01). The data from the evaluations was analyzed using a paired samples, one-way T-test to compare individual performance across both conditions. We hypothesized that projects designed using GenAI would exhibit higher scores on originality and aesthetic qualities, but lower scores on functional qualities. Participants answered questionnaires utilizing a 5-point Likert-scale to gather insights about their experience using AI in their design process. The mean and SD were calculated and correlation analysis performed with the evaluator scores on the design metrics.

3 Results

The aesthetic components of the evaluation rubric included originality, rhythm, harmony, balance, and variety, as well as an overall design quality. The results indicate a statistically significant difference in originality scores, with a value of p = .044 (one-tailed), d = 0.29, 95% CI [−0.35, 0.03], suggesting that GenAI integration resulted in more original design

outcomes, though the effect size was small. The results show no statistical significance between conditions on the other aesthetic variables, nor in the overall design quality metric (see Table 1). There was no statistically significant relationship between GenAI use and functionality. The evaluators were also asked to identify which designs were produced using GenAI, in which they correctly identified GenAI projects only 49% of the time.

Table 1: Summary of the evaluators assessments of the submitted design projects with rubric descriptions. * = statistically significant <.05 threshold

	Traditional Mean	GenAI Mean	t-stat	df	Sig.
Originality: extent the design demonstrates innovative and creative solutions	2.51	2.67	1.72	34	.044*
Functionality: effectiveness of the design in addressing the stated requirements and constraints.	2.87	2.82	-0.40	34	0.34
Rhythm: repetition of elements to create direction and visual movement	2.50	2.67	1.53	34	0.06
Harmony: unity of forms and material in a cohesive whole	2.62	2.65	0.27	34	0.39
Balance: distribution of visual weight to create a sense of equilibrium	2.55	2.58	0.26	34	0.39
Variety: diverse use of materials and forms to provide interest and complexity	2.58	2.55	-0.29	34	0.38
Overall Quality: Wholistic assessment of the quality of the design.	2.52	2.63	0.99	34	0.16

Table 2: Results of the survey given to students about their perceptions using AI

Question	Average	SD
To what extent did AI image generation contribute to the variety of ideas in your design process?	3.34	0.54
Compared to traditional design methods, how would you rate the efficiency of your design process when utilizing AI image generation?	3.09	0.89
How would you describe the integration of AI image generation into your design workflow?	3.31	1.18
How do you assess the overall impact of using AI image generation software on the quality of your design outcomes?	3.4	0.65
How valuable was AI image generation software in inspiring your design concepts?	3.2	0.83
To what extent did AI image generation help you explore new design ideas?	3.45	0.82
Would you consider using AI image generation software again in future design projects?	3.6	1.03

All the participants completed the questionnaire about their experience using GenAI in their process (see Table 2). Students generally responded positively about their use, with the largest variation in responses related to how difficult it was to integrate GenAI into their design workflow and if they would consider using it again. The results were correlated with the evaluator scores to measure if the perception of the impact of AI on the process corresponded with the assessed results from the evaluators. The only significant correlations with substantial strength related to AI helping the designer explore new ideas, which had negative correlations with the metrics of function (-.42) and balance (-.46). An analysis of the results with demographic data of age, gender, and ethnicity was conducted, however there were no statistically significant correlation between these variables and evaluation scores.

4 Discussion

The results demonstrated that the GenAI-integrated method positively influenced the originality of the design outcomes in this study. This supports previous research suggesting GenAI's ability to facilitate the exploration of novel design ideas (SENEM et al. 2023, PLOENNIGS & BERGER 2023, CHEN et al. 2023, JARUGA-ROZDOLSKA 2022), and suggests that GenAI can be an effective tool to stimulate creativity and help designers generate unique forms and designs that may not have emerged through traditional approaches. This does not imply that utilizing GenAI will result in radical design solutions, but rather that it can play the role of an outside source of inspiration to help shape the overall design discourse. Using it in such a way implies that it can be particularly impactful when integrated as a design development tool early in the process.

There was no statistically significant difference between the GenAI-integrated and traditional processes in evaluating the other aesthetic components or the overall design quality. This demonstrates that GenAI has the potential to act as a complementary tool to enhance creative thinking without substantially impacting design quality or producing sterile results. It appears that the designer's role in the process remains important to the final outcomes, and that human design skills, including decision making, are still critical factors in design quality and composition, regardless of the use of GenAI. Despite rapid advancements in artificial intelligence, this implies that the traditional design approaches will remain important and may not be wholly replaced by the assistance of GenAI, rather the GenAI-integrated process may only be as successful as the designer utilizing it.

While we hypothesized that the GenAI-integrated process would result in lower functionality within the design, this was not the case, indicating that GenAI use alone does not inherently lead to impractical solutions. This was a concern raised in prior research regarding GenAI's lack of real-world contextual awareness, which may result in visually compelling but impractical designs (CHEN et al. 2023, JARUGA-ROZDOLSKA 2022). As noted with the aesthetic outcomes, having GenAI and the designer simultaneously in-the-loop appears to negate the potential negative impact GenAI-influenced designs might have on functionality. Therefore, while GenAI might enhance originality in design, other evidence clearly demonstrates that responsibility remains in the hands of the designer to ensure aesthetic and functional success.

Student opinions on the ease of integrating GenAI into their workflow produced the largest variation in responses. This may reflect a broader uncertainty about the proper integration of GenAI in design, but may also highlight that immature designers have not yet developed the

capacity for robust internal dialogue with their design (and by extension GenAI), and that they may find it difficult to utilize the generated images and ideas because they struggle to integrate those visual references with their design approach. Donald Schön (1987) theorized that design is a reflective process akin to a conversation. In this case, GenAI, using interaction driven by natural language processes, should be ideally suited for integration within discourse between the designer and their design, but it requires the designer to have the capacity to engage at a level of reflection and introspection with their design and process to leverage the natural interactions that AI applications can provide. The suggestion that such immaturity was experienced by some students in their interaction with GenAI might also be inferred by the correlations of higher reported levels of GenAI helping explore new ideas resulting in lower scores from evaluators on both function and balance. It is possible that students became enamored or aesthetically hoodwinked by the GenAI's outputs and failed to engage in a rigorous process of reflection on their GenAI-influenced design, resulting in less ideal design outcomes. Students who used GenAI in a more reflective and nuanced way were more likely to report lower levels of influence as they remained more "in control" of the process.

The findings invite a broader discussion on GenAI's impact in academia and practice. Using GenAI as an "ideation partner" may allow designers to explore a broader scope of form and materiality before transitioning to the more technical and site-specific phases of design, illustrating how GenAI might shift the emphasis of early-stage design from the manual production of imagery and ideas to the curation and refinement of conceptual possibilities. However, this research underscores that GenAI is most effective when used as a supplemental tool for ideation and is not a substitute for the designer's critical judgment. This suggests the human remains the primary driver maintaining functional and creative oversight of the process. It is likely that it will be some time before a widely accepted workflow with AI emerges and, whatever that workflow may be, it will most likely exist along a spectrum of use and integration between the designer and AI.

For academia these findings signal a necessary pivot toward GenAI literacy within the design studio, but do not call for a wholesale rethink of our design processes or instruction. Rather than viewing Gen AI as a threat to traditional skills, curricula should focus on teaching students how to effectively manage the "human-in-the-loop" process. This involves developing a pedagogical framework where students are evaluated not just on the final output, but on their ability to critically select, modify, and justify GenAI-generated concepts based on site constraints and programmatic goals.

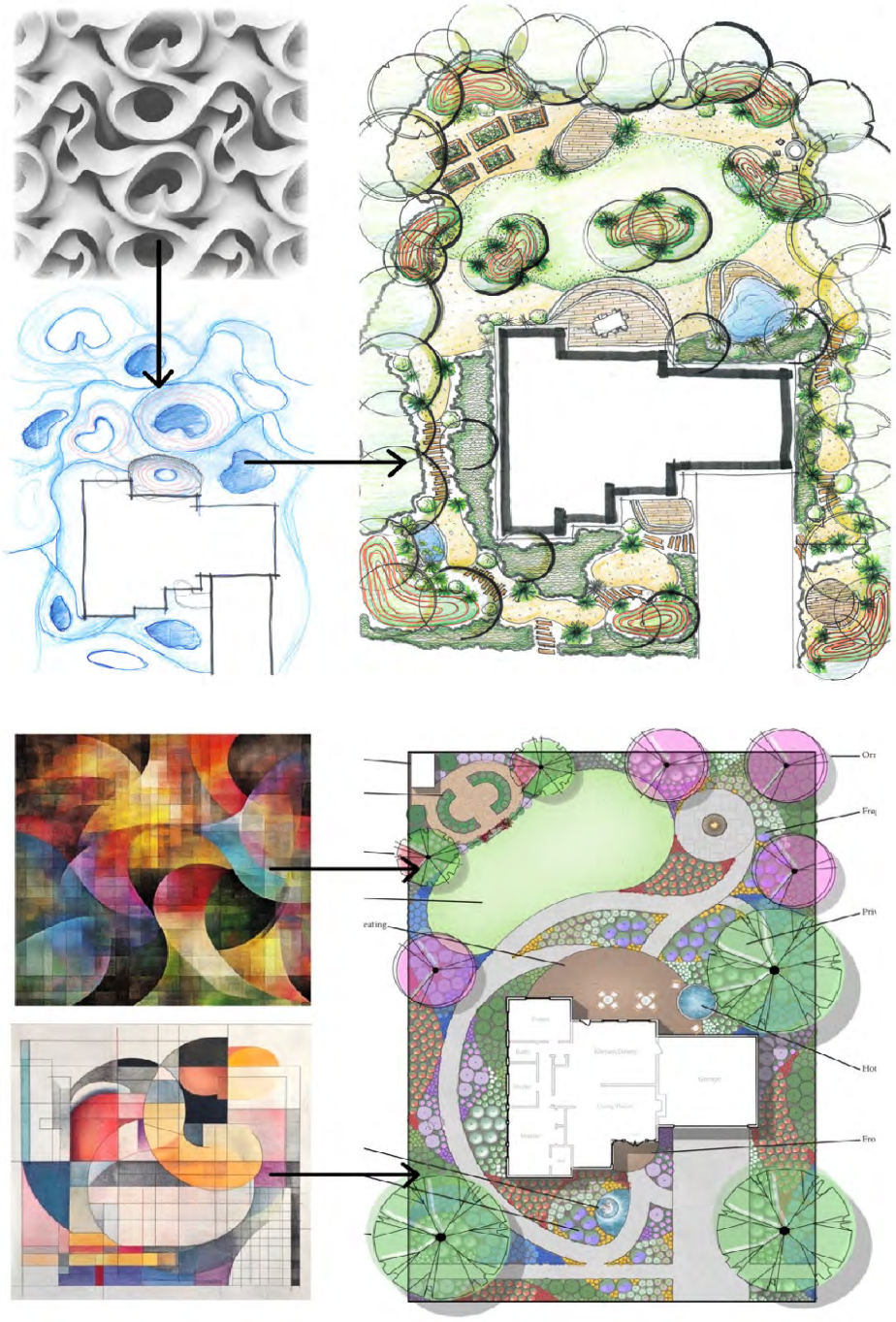

Fig. 1: Examples of final student designs with the AI prompts and design processes associated with them

There is a clear need to balance the teaching of foundational skills alongside the strategic use of prompting and iterative refinement, ensuring that students do not become overly reliant on automated outputs at the expense of developing their own design maturity and thus their ability to evaluate GenAI outputs.

Finally, the use of platforms like Midjourney in a design context is not without ethical and pedagogical risk. Ethically, the black-box nature of these models raises valid concerns regarding intellectual property and the potential for reinforcing cultural or aesthetic biases in the built environment. These appear to be manageable with careful prompting and knowledge of more advanced generative processes (such as seeds and styles), but this requires a level of awareness and management that many designers, and especially students, may not be willing to commit to. Pedagogically, there is a risk that the ease of generating high-fidelity imagery may tempt students to bypass the rigorous iterative problem-solving phase of design, leading to "hallucinated" landscapes that are visually seductive but aesthetically poor or functionally, ecologically, and structurally unfeasible. Educators must therefore emphasize that while GenAI can simulate the appearance of a completed project, it lacks the underlying spatial and biological intelligence of a trained landscape architect, necessitating a critical approach to outputs. Therefore, analytical and soft skills are likely to become even more valuable to a landscape architect in the future.

5 Limitations

A primary limitation of this study was the use of students from a single university class as study participants. This resulted in a fairly homogenous sample group in regard to design experience and educational background. Repeating this study with a more heterogenous sample may reveal demographic differences between how different groups might use and integrate GenAI. Another limitation was the lack of access to each student's Midjourney account so it was not possible to track the prompts used, the number of prompts generated, or the amount of time students spent within Midjourney. Collecting this data would have provided valuable insights into how students worked in a human-AI collaborative design process and is recommended for a future version of this study.

6 Conclusion and Future Work

In conclusion, the findings of this study suggest that GenAI-integrated design processes have the potential to enhance creativity in the landscape architecture design process in early-stage creative exploration. However, GenAI integration did not significantly impact the functionality, aesthetic composition, or overall design quality of the student work. These results align with previous research, reinforcing the idea that GenAI image generators, such as Midjourney, work best as a tool that supports designers in the iterative process of form exploration, rather than serving as a standalone design solution.

Student opinions toward GenAI use in the landscape design process were generally positive, with many indicating that GenAI image generation aided their creative exploration and that they would consider using it in future design projects. However, the correlation analysis revealed a disconnect between student perceptions and expert evaluations, suggesting that students may have overestimated or been misguided by GenAI in their design decisions. This

emphasizes the need for further research and education on how GenAI-generated imagery is critically assessed and integrated into design workflows.

Ultimately, this study highlights the advantages and limitations of AI in the design process. While GenAI tools like Midjourney can provide form inspirations and offer the rapid visualization of design concepts, they cannot replace the role of the designer in making informed, contextually grounded, appropriate decisions. Future research should explore ways to refine the integration of GenAI in the design process, specifically how these tools can better support both creative ideation and functional site planning.

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Next-Gen Landscape Design: Agentic AI + Digital Twins

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Abstract: The complexity of issues confronting landscape architects and other environmental designers, in the face of the global polycrisisvare immense and growing. Artificial Intelligence (AI) tools, may represent a panacea, but they are still very little beyond infancy; results across many domains are so far quite mixed; and limitations and concerns are abundant. In this context, several different but related emergent technological advances do seem likely to be key drivers of the next generation of AI-enabled computer-aided-design tools intended to help design thinking and manage real-world complexity: 'Agentic AI' (AAI) platforms connected to 'Digital Twins', esp. 'Digital Twin Earths' (DTEs), with 'Model Context Protocol' (MCP) and 'Retrieval-Augmented Generation' (RAG) used to control and constrain the AI agents. Following a brief description of these technologies and their foundations, I explore some application possibilities by re-visiting a decade-old 'System for Geodesign' with AAI, MCP, RAG, and DTE integrated, and outline an updated prescription for a technologically enhanced and enabled next-gen 'AAI+DTE' design system (not just for geodesign). A highly simplified prototype agentic system implementation is described.

Keywords: Next-Gen Computer-Aided Landscape Design, Agentic AI, Digital Twin Earth, Retrieval-Augmented Generation, Model Control Protocol

1 Introduction

As the big-data, scale-hopping, information-processing, multitudinous detail-managing, and time-consuming collaboration-choreographing demands on digital landscape architects continue to grow, especially in the face of global environmental issues, the promise of computer-aided design to alleviate some time-consuming and repetitive tasks so as to give designers time and space to design is evermore seductive. From Sutherland's seminal SketchPad, through 2D and 3D CAD, GIS, Remote-Sensing and Image-Processing, GPS and then BIM, and now AI-in-CAD, some productivity gains have been achieved. Over the same time span, the complexity of issues confronting environmental designers, and the complexities of marshaling design and construction projects in the real world, have been even further increased. The current explosion of AI, with its similar promises, is still in its infancy; results are so far mixed; concerns are real; and speculation is rampant.

For the past few years, it has been apparent that the long-awaited potential of Artificial Intelligence (AI) as foreseen by (TURING 1948), (MINSKY 1986), and (SIMON 1996) may have begun to be delivered (albeit with some already apparent downsides!). The explosion of Machine Learning (ML), Large Language Models (LLMs), Generative Pre-Trained Transformers (GPTs), Generative Adversarial Networks (GANs), Diffusion Model Generative Pre-trained Autoregressive Diffusion Transformers (GPDiTs), Model Context Protocol (MCP), and Retrieval-Augmented Generation (RAG), along with other techniques and platforms including ChatGPT, Gemini, Claude, DALL-E, Stable Diffusion, and now a whole host of other technologies and acronyms, in just a few years' time, has absolutely rocked worlds – of de-

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sign (CANTRELL et al. 2021), construction (ABIOYE et al. 2021), education (BOWEN & WATSON 2024), communication, entertainment, and everything else in between.

In recent years, a number of papers published in JoDLA and elsewhere have chronicled the emergence of AI in Landscape Architecture (BRAIDEN et al. 2025), (XING et al. 2025). This emergence is proceeding so rapidly that already these early reviews and experiments seem almost quaint.

What most AI at this moment in time (2025) is already very good at doing includes organizing, summarizing, modifying, and even synthesizing textual data and responding to natural language prompts, based on a huge library of background knowledge in ways which are usually coherent, well-structured, plausible, and believable, even if not always factually true. And, to a somewhat lesser extent, doing the same for images, music, computer code, and other media. Its facility with interaction and apparent understanding of the meaning of the text prompt (s) it is responding to are deceptively good, notwithstanding that we know, in fact, there is no real understanding or reasoning, only statistical similarity and likelihood, at work; and despite the many flaws and potential problems with the current technologies, which depend on a large body ('corpus') of training samples, possibly biased or incomplete, for all of their power.

As to whether and how the GenAI programs may be designing, there is much discussion; on this topic, ChatGPT-4.1 itself says: "[Generative AI]'s processes lack intentionality, contextual awareness, and critical reflection that are central to design as traditionally understood."

This observation is behind the oft-repeated suggestion that "there needs to be a human in the loop" (WIKIPEDIA 2025), and the assertion that "co-design between humans and machines is the logical evolution of computer-aided design". There is good evidence that already, AI tools *can* aid design and designers in various ways, and so belong in the modern Computer-Aided Design toolbox. How these tools will become sharper, more accurate, and effective, more widely and creatively used, etc., will doubtless continue to consume the Digital Landscape Architecture community, along with much of the rest of the world. The goal of the tools in the CAD toolbox is no longer just to "free designers from burdensome and repetitive tasks", and their promise is not to *reduce* complexity, but rather more critically: to help *manage* complexity.

Two important recent developments in related technologies will likely be central in this evolution: *Agentic AI* (AAI) platforms (WANG, L. et al. 2024) and Digital Twins, especially *Digital Twin Earths* (DTEs) (GRIEVES & VICKERS 2017).

These two emergent technologies promise to be mutually supporting and truly transformational for digital landscape architecture in the rest of the 21st century.

1.1 Agentic AI (AAI)

The 'chat'-style Generative AI many people are most familiar with now is a highly episodic interaction, initiated by a specific prompt, which elicits a response, and then often a refined or follow-on prompt spurred by some deficiency in the response, or some new avenue of inquiry, and so on. The human is not just in the loop but is leading the interaction at each step; the AI is mostly responding (or sometimes leading with canned "Do you want me to provide or explain anything in more detail?" questions). And there is effectively just one AI in the loop – typically, a LLM 'foundation model' trained on some very broad corpus of

training samples. By contrast, a*gentic systems,* given high-level goals and other directives in initial prompts, can become proactive, goal-driven, and collaborative, using generative AI and other special-purpose software tools and APIs as components in a larger, self-directed, multi-step process. These agents may also be aware of change, and so can monitor changing contextual information, whether from sensors, or websites, or other sources. AAI systems aggregate several individual AI agents (AIAs) together, in a communicating network, often along with an 'orchestrator' or dispatcher agent (ANTHROPIC 2025).

Two additional developments promise to further control AI generative capabilities, and reduce hallucination, by adding an element of algorithmic/procedural workflow control via Model Context Protocol (MCP) (ANTHROPIC 2024); and factual lookup from one or more specialized / tailored databases via Retrieval-Augmented Generation (RAG), (LEWIS et al. 2020) which can provide the independent agents each with a suitable database of domain-specific information for their intended specialization. RAG-based agents can be much simpler than the full-bodied LLM behind generative AI; and their performance can be guided by rules, algorithms, and workflows managed by MCP, which can function like conventional computer code, running procedures, writing to databases, sending emails, and querying live APIs, rather than just probabilistic pattern matching.

1.2 Digital Twins (DTs)

Digital Twins are virtual replicas of real-world systems, capable of reflecting and predicting system behavior, such that ordinary and unusual conditions can be simulated computationally, monitored, and analyzed, and used to predict system behavior over time, under stress, etc. (WANG et al. 2024, HAZELEGER et al. 2024). First named and formalized in the context of modern aircraft design, construction, and operation, the idea has been spread to other domains and scales – from the human body, or individual organs therein, to the building-, region-, watershed-, and even planetary-scale – including the specially named Digital Twin Earths (DTEs). Perhaps the most advanced such efforts are Europe's Destination Earth (DestinE) (THE DIGITAL EUROPE PROGRAMME) and NASA's Earth System Digital Twins (ESDT) (ESA) initiatives; there are others, such as Google Earth Engine (GOOGLE 2024), from various sources (NASA), (NVIDIA) with various aims. DTEs can generate literally mountains of data, and so the interfaces for querying, analyzing, and storing their outputs is a rapidly evolving branch of technology. In more familiar traditional computer information terminology, AIAs contain *algorithms* or *procedures*, and the digital twins are databases – but in both cases, they are each hybrid, containing a combined mass of factual and procedural knowledge.

Specialized AIAs are especially well-suited to interface with special-purpose big data, such as with DTEs, giving rise to the following 'AAI+DTE' System proposal:

2 AAI+DTE Applied to Ervin's 'System for Geodesign'

A 'System for Geodesign', (ERVIN 2011) was originally presented at the DLA Conference as a proposal for a system of 15 distinct 'modules', which in combination would provide, in the author's view, the technological support – integrating CAD, GIS, database, version management, simulation, programming, and other functions – required for full-fledged geodesign as

envisioned by (STEINITZ 2012). At the time, these modules were envisioned as tools such as computer users were accustomed to using; one at a time, each with limited and isolated functionality. This multi-module framing provides a useful test case to explore the design and eventual implementation of a suitable Agentic design system, and its AI Agents. Below, with some modifications to the number, order and the names as originally presented, are descriptions of 16 proposed Agents in the Agentic AAI+DTE approach:

(*Note that this is still mainly a thought-experiment and proposal; these prescriptions for agentic structure and behavior use 'could' and 'can', for now, rather than 'do' or even 'will'. An exploratory prototype instantiation of this outline proposal is described in the next section.)

1. Environment/Context-Base: The BaseMapAgent

With access to a robust DTE, the BasemapAgent could retrieve relevant layers for the location (s) and scale (s) required; and identify relevant contextual information. The BasemapAgent could automatically ingest, align, and integrate new data sources (imagery, sensor data, maps, etc.), even in real-time, working together with the Library Agent (#14).

2. Elements (Objects, Groups, Concepts): The ElementAgent

This agent maintains the working list of design elements, both concrete and abstract; and could propose site-appropriate landscape elements (landforms, structures, vegetation, paving, furniture, irrigation systems, etc.) based on context and goals, with reference to relevant libraries and catalogs. AI image recognition agents can classify and tag objects from aerial imagery, lidar, or text descriptions – enriching the elements database for design use.

3. Configuration: The ConfigAgent

This agent, using generative approaches (e. g. diffusion or GAN models) can create and modify alternative site configurations (paths, layouts, plantings, floorplans, etc.) responding to stated requirements or preferences. The ConfigAgent working with the ConstraintAgent could create, compare, and propose multiple feasible "what-if" scenarios. Note: This is still aspirational; such graphics capabilities and spatial reasoning are currently the least well-developed of AI technologies, and will require serious development work.

4. Constraints: The ConstraintAgent

The ConstraintAgent could receive high-level constraints directly from the human designer, as well as mine policy documents, local regulations, and site analysis to interpret and apply relevant constraints automatically. It could detect conflicts, and alert the human in the loop, or mediate between conflicting constraints (e. g., ecological vs. recreational goals), recommending optimized or satisficing resolution strategies.

5. Analyses: The AnalysisAgent (s)

This agent could conduct a wide range of geospatial and performance analyses, from standard GIS operations to more complex assessments like visual quality, habitat suitability, microclimate modeling, etc. It could proactively identify and run relevant analyses based on the design context and goals, highlighting potential issues for the human designer without needing to be explicitly prompted for each test.

6. Simulations: The SimAgent

The SimAgent could provide experimental dynamic analyses of proposed configurations and elements; using the resources of digital twins and procedures such as Computational Fluid Dynamics (CFD) and others to model dynamic processes over time, such as water flow, vegetation growth, energy performance, or pedestrian movement, etc. It could run multiple parallel simulations to compare the performance of different design alternatives under various future scenarios, using predictive models to forecast long-term ecological and social outcomes; as well as producing animations and other graphic artifacts.

7. Dashboards: The DashBoardAgent

This agent could generate and manage dynamic, real-time visualizations of the design's key performance indicators (KPIs). The DashBoardAgent could learn which KPIs are most important to the design team and create customized dashboards that clearly communicate progress towards project goals, working with the Abstraction and Diagram agents, and pulling data from both the Analysis and Simulation agents.

8. Version Manager: The VMAgent

The VMAgent, using version management technologies developed in the software industry, could track and manage the evolution of the design, capturing not just incremental saves but also significant branching points and design decisions. It could compare different versions, highlighting substantive changes in form or performance, and could suggest when prior abandoned solutions might have content applicable to a current design problem.

9. Time/Dynamics Manager: The TimeAgent

This agent would be responsible for modeling and integrating time-related aspects of the design. It could simulate and visualize phenomena across multiple temporal scales, from the daily cycle of light and shadow to seasonal vegetation changes and the long-term impacts of weathering or climate change. The TimeAgent would need to work closely together with the SimAgent.

10. Level of Abstraction (LOA) Manager: The AbstractionAgent

The AbstractionAgent would manage the various phases of the design project, and their associated representations, from the most abstract (initial programs, text representations, and schematic bubble diagrams, e. g.) to most concrete (3D models, working drawings, and detailed specifications). It would be aware of the stated design goals and intentions, and track the implications of those on specific, concrete proposed elements, layouts, and instantiations, and vice-versa. It can be used to help ensure that changes made at one level of detail are appropriately propagated to all other levels.

11. Diagram Manager: The DiagramAgent

Calling upon generative AI, the DiagramAgent could automatically translate complex data and spatial relationships into diagrams, charts, and conceptual graphics, for presentation to external decision-makers or on the design Dashboard. This agent could assist in communicating the design intent and performance to stakeholders, generating visual explanations for system dynamics or analysis results. Note: as mentioned above, as of this writing (2025), Gen AI is rather good at generating vivid and compelling illustrations, but is not very good at all

at making clear diagrams, working drawings, or useful visual explanations – basic flowcharts are about as good as they get, and even then they are not yet always coherent; this remains an area for deep research and innovation.

12. Algorithmic Interface: The CodeAgent

The CodeAgent would provide a natural language interface for scripting and algorithmic design, allowing designers to generate custom functions without writing code manually. It could also respond to requests for code solutions from other agents and proactively search for and suggest novel algorithms or computational techniques from external libraries to solve unique or complex design challenges**.** In contrast to #11 above, this is a task that GenAI is already very good at.

13. Text/Media (Hyper-Annotations): The MediaAgent

This agent would link design elements to a rich network of related information, such as internal and world-wide web documents, including reports, images, and videos. It could automatically scan and tag documents for relevance and create hyper-annotations within the design model, providing contextual information built into the design documentation, so that the Dashboard manager could for example have multiple live links for deeper dives into relevant information.

14. Library: The LibAgent

The LibAgent would curate and manage extensive libraries and catalogs of design components, precedents, materials, and details, providing search and recommendation functions based on project context and constraints. Furthermore, it could provide materials and exemplars to generative models to create novel, context-appropriate design elements. The LibAgent would need to work closely with the ConfigAgent and ElementAgent, offering up elements and configurations from the Library, and storing newly developed or used ones for future use.

15. Collaboration tools: The CollabAgent

This agent would be responsible for facilitating teamwork among human designers, other stakeholders, and other AI agents, managing workflows, tracking tasks and calendars, and offering possible collaboration tools. It could mediate potential conflicts by summarizing differing viewpoints, highlighting areas of consensus, and proposing integration strategies for divergent ideas. This too is an area where AI is already quite functional.

16. Design Methods Coach: The DMCoachAgent

The DMCoachAgent would observe the overall design workflow and offers expert guidance on the process itself. It could recommend appropriate design methods, suggest timely analyses, and provide meta-level feedback on the team's progress. Depending on the state of the Dashboard, new agents may need to be acquired or spawned, and various functioning agents could be analyzed for their effectiveness, and replaced or re-written, by the DMCoachAgent and CodeAgent working together, according to some algorithm for evaluating ‘goodness’, ‘utility’, or ‘progress’, etc. Over time, the DMCoach could learn from experience, evaluation, and recording, what works or has worked well in what situation (s), building a library of ‘Learned Design Intelligence’.

3 Discussion: How Might These Technologies Work Together?

This proposal for a multipartite system is basically a reiteration of a familiar design office structure – a combination of experienced senior human designers and leaders, supported by varying numbers of junior staff and consultants. Different AI agents need not only different knowledgebases, priorities and precedents, but also different worldviews, procedures and algorithms. Although the above prescription identifies 16 variants, their exact number, makeup, training, and specializations will need to change and evolve with contexts, programs, client needs, and emergent priorities. For example, there is no 'ClimateMitigation' expert, or 'Sustainability' agent defined; this proposed system is at one abstraction level up from that. Climate mitigation criteria, plant selection, and other thematic or needs-based design criteria, will need to be individually addressed per design or program, by elements, configurations, analyses, simulations, collaborations, etc. However, one or more new generic agents may yet be required; for example, a dedicated 'Conductor' agent is likely to be essential in building an effective AIA design system (Fig. 1).

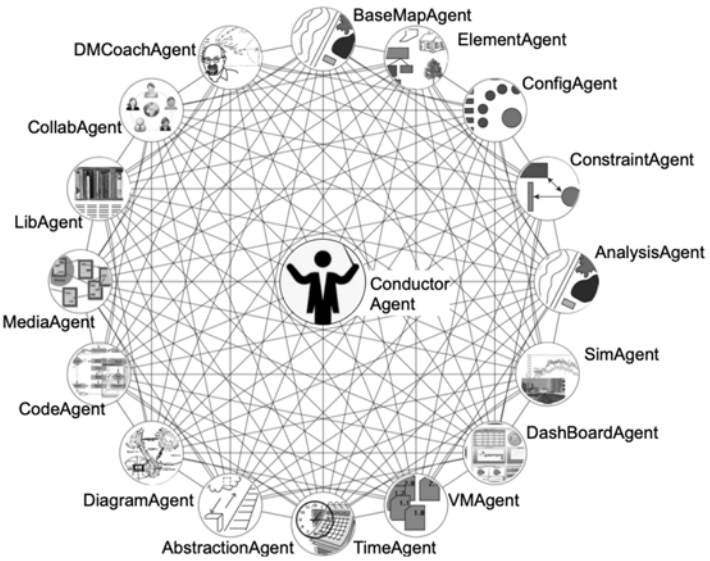

Fig. 1: 16 Distinct Generic Interconnected AI agents, all connected to a central Conductor agent

Design thinking and design processes have always been characterized by a tension, and some amount of cross-fertilization, between creative/imaginative/qualitative/intuitive on the one hand and'systematic/quantitative/evidence-based/rational on the other (the latter often supported by the engineering disciplines, the former by artistic practices); as well as between general/universal and site-specific/customized ideas and approaches. This can be seen already as a kind of *co-design*; the proposed AAI+DTE agentic system further crystallizes these combinations and competing/collaborating forces.

The multipartite structure of the proposed agentic system is designed to help manage complexity, by a combination of multiple agents and multiple specializations, just as in a big international, interdisciplinary design & construction firm; but soon accessible to a small 3-person firm, as well. This promise will depend very much on the development of specialized AI agents from within landscape architecture and allied disciplines, such as civil engineering, hydrology, conservation, forestry, transportation, etc.

Digital Twin Earths, which to date are mostly government-sponsored, are under active development. Connecting CAD, BIM and Agentic AI systems to their outputs from active sensors and archival databases is still a daunting challenge for designers. But this too will continue to evolve, and the access will inevitably become easier, just as the size and scope of data available will expand. Access to real-time data will increasingly become a part of responsive and responsible landscape design and will require the integration of specialized APIs and AI agents to achieve it.

Artificial (computerized) intelligence as a research and development effort is both broad and deep. At present, generative AI is still too prone to hallucinating (lying/fabricating) to be truly useful in any fact- or reality-based situation without a lot of human handholding. Because of the strictly statistical basis of its intelligence, it is usually plausible and sometimes even right, often enough to fool many into over-estimating its veracity and hence utility. There is real peril in this, and possible harm; and potential bias, political interference, and other ethical concerns plague even the largest training samples (NARAYANAN & KAPOOR 2024), (HANNA et al. 2025). But there's no denying that the combination of a huge accessible data base ('everything measurable on planetary sensor systems', or even 'everything on the World-Wide Web', e. g.), coupled with highly scalable pattern recognition and generative abilities, is a powerful force.

4 Proof-of-Concept Development: A Working AAI Prototype

In mid-November 2025, Google introduced AntiGravity (GOOGLE 2025), a new "agent-first" AI-powered Integrated Development Environment (IDE) for agentic software development. Using this system, the author has developed a modest but functional proof-of-concept prototype agentic system. This prototype represents a highly simplified instantiation of the proposed system architecture, implementing only three agents: a Conductor agent (orchestrating overall workflow), an Element agent (managing landscape components and materials), and a 'Sustainability' agent (not one of the core agents in the spec, but suggested by AntiGravity, and implemented as an experiment) – and all of those quite rudimentary. The system runs on a Mac Studio desktop computer using an open-source development stack (Python, PostgreSQL, and associated RAG and MCP libraries) with API connectivity to OpenAI's language models (ChatGPT-4o). Domain knowledge is provided through a small vector database populated with project examples scraped from a commercial landscape architecture office's public website, creating a minimal but authentic corpus of professional precedents for retrieval-augmented generation.

Despite its limited scope, this prototype successfully demonstrates the core principles of the agentic architecture proposed herein. The Conductor agent receives natural language design prompts, decomposes them into sub-tasks appropriate for the specialist agents, coordinates

their activities, and synthesizes their outputs into conversational design suggestions. The Elements agent queries the vector databases to identify contextually appropriate plant materials, site furnishings, surface treatments, etc., based on project requirements and precedent similarity, while also generating suggestions without being specifically prompted. The Sustainability agent analyzes the proposal from the Elements agent and makes suggestions for alternatives. The interaction among these agents exhibits genuinely agentic behavior: the system maintains conversational context across multiple exchanges, requests clarifications, prompts for additional info, proposes alternatives based on retrieved precedents, and iteratively refines outputs in response to feedback.

As an example, consider a proposal for a public park with an emphasis on walking. The LibAgent agent might identify as a precedent the Imperial Garden at Tokyo, and its circulatory approach of a main path connecting entrances and exits, with subsidiary smaller paths branching off in loops. Passed to the AbstractionAgent, and the DiagramAgent, and with consultation from the BaseMapAgent, this could generate a simple circulation diagram; and from this the ConfigAgent could identify suitable entrance and exit locations. The ElementAgent could suggest plant materials, benches and lighting fixtures, which the ConfigAgent could locate.

Note: The creation, analysis and maintenance of graphical components – line diagrams, layout drawings, perspective renderings and the like – remain the most difficult and problematic for the current generation of AI tools, but there is no doubt that these limitations will begin to be overcome in the next few years, especially with impetus from disciplines and projects outside of the purview of landscape design. This – real effective ‘CAD’-integration – is the development most still-needed for the full flowering of the agentic design system imagined and proposed herein. The simple prototype developed in AntiGravity can handle the logical flow and the textual narrative, but not yet the drawings – especially the diagrams!

The prototype's technical implementation highlights both the current feasibility and the many remaining challenges of building domain-specific agentic systems. On one hand, contemporary tools make it surprisingly easy for a single developer to assemble a working multi-agent system in a matter of weeks. The combination of capable foundation models (LLMs accessed via API), vector databases for semantic retrieval, generative on-line systems like those from OpenAI and others, and orchestration frameworks like Antigravity dramatically lowers the barrier to entry for experimental agentic applications. On the other hand, scaling up this minimal three-agent system prototype will require substantially more time and expertise. The vector database, while demonstrating in principle the viability of RAG for domain-specific design knowledge, remains small and narrow; connecting to comprehensive Digital Twin Earth data sources, integrating simulation capabilities, and ensuring reliable performance across diverse project types will require substantially greater effort, infrastructure, and investment.

5 Conclusion

This paper began as an effort to reconceptualize the 2011 'System for Geodesign' in light of transformative developments in artificial intelligence, geospatial technology, and environmental data infrastructure. The resulting proposal – a multi-agent Agentic AI system integrated with Digital Twin Earth resources – represents a speculative vision, arguing that such an architecture could address the escalating complexity, data intensity, and collaborative demands of contemporary landscape architecture practice.

The development of a working prototype, however modest, is a step from the purely hypothetical toward the increasingly feasible. The ability to build this prototype on Google's Antigravity platform also reveals something important about the trajectory of AI development. Antigravity is itself an Agentic AI system – a generalized platform for orchestrating multiple specialized agents toward complex project goals – that happens not to be domain-specific to landscape architecture. Creating a landscape-focused agentic system within Antigravity demonstrates a kind of fractal recursion: an agentic architecture building an agentic architecture, with the same organizational principles applying at both the development-tool level and the application level. This pattern is not unique to Antigravity; similar multi-agent orchestration frameworks are emerging across the AI development ecosystem, suggesting that the agentic paradigm is becoming a standard architectural pattern for complex AI-enabled work (and, as a side-effect, with fewer 'humans in the loop' of coding and software development!)

The challenges ahead remain substantial. Scaling from three agents to sixteen, from a small precedent corpus to comprehensive integration with Digital Twin Earth resources, from schematic suggestions to full design documentation and effective CAD-integration, and from single-user prototypes to collaborative professional tools, will require significant technical development, disciplinary knowledge formalization, and careful attention to the practical and ethical dimensions of AI-augmented design practice. One of the more intriguing, and challenging aspects of the proposed system is the ability for it to learn over time, not just about elements and landscapes, but also about patterns of design strategies, building up a database over time of 'Learned Design Intelligence' from its use.

The landscape architecture profession has absorbed and responded to technological shifts for decades; the prototype described here and the platforms on which it was built are just the latest stage in the evolution of 'computer aided design'; and they are still fundamentally lacking. In spite of the much-publicized generative facilities with text and graphics, most AI foundation models are still quite primitive with respect to graphical representation and spatial reasoning – essential for landscape architects. Another principal missing ingredient in most current AI systems is algorithmic and rule-based logical reasoning and calculating components, that surely will necessarily underlie the ultimate goal of Artificial General Intelligence (AGI) (GOERTZEL & PENNACHIN 2007). This is the premise of the latest developments in *neuro-symbolic AI* (D'AVILA GARCEZ & LAMB 2023), (of which RAG is an early example) in which the neural-net pattern-recognition and statistical generative synthesis tools are combined with more algorithmic and rule- and logic-based symbolic approaches, including appropriate constraints and 'guard-rails', and so less prone to fabrication, and so more defensible and reliable. Current agentic platforms, development IDEs like AntiGravity, and RAG and MCP implementations are all still in their infancy. The next developments in this synthetic environment will provide even better support for next-gen computer-aided design, as design needs both rules and rule-breaking, both dreaming and solid structural foundations;

and effective performative designs will require access to real-world dynamic sensor data, and may be accomplished by robotic ‘actuators’ in the field.

Perhaps not all landscape designs or design processes need to be deterministic, just as not all landscape architects need to be digital landscape architects – but many of them, for infrastructure and other large and public works, benefit from being so. A well-formed neuro-symbolic AIA agentic system, with RAG/ MCP augmentation, connected to a database repository of reliable domain-specific information, and a robust DTE – along with one or more humans in the loop (Fig. 2), to provide ‘intentionality, contextual awareness, and critical reflection’, among other things – is a likely candidate for delivering such tools to the next generation of digital landscape architects and planners.

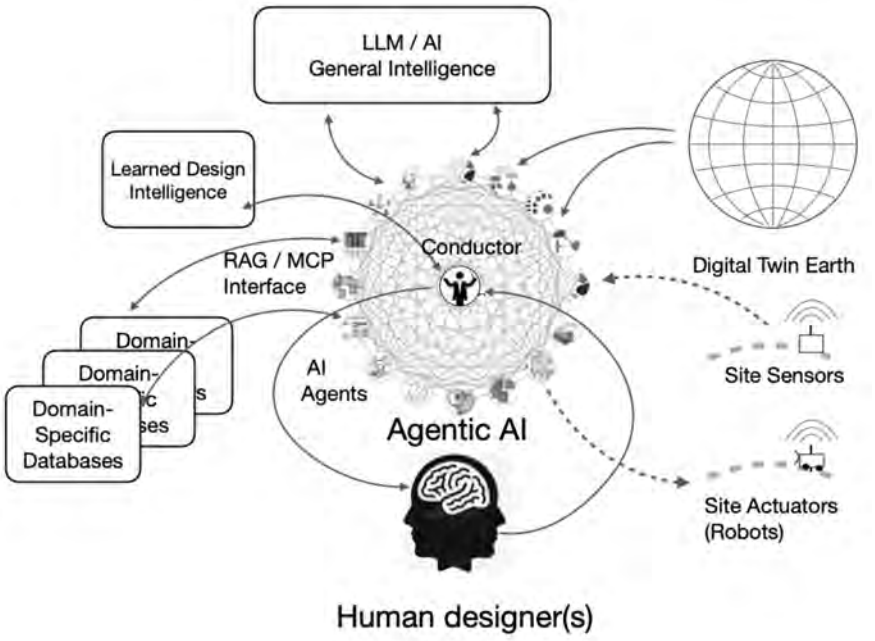

Fig. 2: Conceptual Architecture of the AAI+DTE System. This diagram illustrates the functional ecosystem of the proposed Agentic AI design system. At the center is the Agentic AI cluster, featuring the network of specialized Agents (e. g., Layout, Elements, Simulation) orchestrated by a central Conductor agent. The Human designer (s) ("human-in-the-loop") interface primarily with the Conductor to provide intent, goals, and critical review. The agents’ cognitive capabilities are powered by LLM / AI General Intelligence (foundation models), supplemented by Learned Design Intelligence (specific design heuristics and rules). To ensure accuracy and reduce hallucination, the system utilizes a RAG Interface (Retrieval-Augmented Generation) and Model Context Protocol (MCP) library to provide algorithmic flow-control and to fetch verified information from Domain-Specific Databases (containing precedents, codes, and material libraries). Finally, the design is grounded in real-world context through connections to a Digital Twin Earth for environmental data; and Site Sensors / Actuators, not addressed in this paper, can provide on-site monitoring and machine-controlled (‘robotic’) physical interventions.

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The Landscape Architect as Developer and Designer: Optimisation and Control of Diffusion Models for Landscape Architecture

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Abstract: The integration of Generative Artificial Intelligence (GenAI), particularly image-generating AI, into landscape architecture marks a decisive step in the digital development of this discipline. This work examines how diffusion models can be demonstrably optimised and controlled to support creative and site-specific design processes within landscape architectural workflows. Focusing on the training and fine-tuning of AI models, the study investigates how customised data and proprietary parameters influence the generation of spatially specific images and design results. A conceptual and technical framework developed in this work, adapted to the open-source generative AI model Stable Diffusion, provides the basis for the practical implementation of training using Low Rank Adaptation (LoRA) and DreamBooth as fine-tuning training methods. This study adopts the classical design process as a holistic framework: Three specific learning tasks – location, concept control and look – define the experimental setup and function as identifiable integration points within the design workflow. The AI models are evaluated both qualitatively and quantitatively through these learning tasks. This paper contributes a structured framework for controlling diffusion models in landscape architectural design. It further demonstrates how these control dimensions can be operationalised within practical design tasks. By examining the interaction between human intent and algorithmic interpretation, this work reveals new possibilities for creative control and optimisation within AI-driven design workflows and positions landscape architects as both designers and active developers of their tools.

Keywords: Generative Artificial Intelligence (AI), diffusion Models, landscape architecture design, fine-tuning and model control, low-rank Adaptation LoRA

1 Introduction

This paper examines the potential for generative AI to be adapted for landscape architecture. The aim is to investigate how landscape architects, as interdisciplinary practitioners, can influence the development of AI in their field. The objective of the study is to benefit from customised models in landscape architecture in order of optimise processes and gain better control over outcomes. The overarching research question is: "How can AI models be customised and used in collaboration with human designers to accurately capture, manage, and creatively develop site-specific, conceptual, and visual aspects in landscape architecture?"

The present study is distinguished by its specific focus on training and fine-tuning of diffusion models in landscape architecture, emphasising on controllability and optimization. By systematically examining learning tasks, this study demonstrates how AI can be integrated into the landscape architectural context – highlighting concrete points where landscape architects can appropriate AI as a creative tool and exercise greater control over design outcomes. It contributes to research by providing a detailed framework for training, evaluating, and optimizing AI models customised to specific tasks in landscape architecture.

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2 Generative AI-Models in Landscape Architecture

2.1 Custom Models: Optimization and Controllability

In landscape architecture, generative AI methods further facilitate the transition of the traditional process of pen and paper creation of design variants into the digital realm (WALLIS & RAHMANN 2016). AI research is now broad in scope, ranging from the use of image-generating AI for visualisations (LI & AMOROSO 2023), the creation of 2D assets (FERNBERG et al. 2023) and applications of GPT models for plant selection (GEORGEet al. 2024) to the training of AI (GANs and diffusion models) with a focus on planting plans (SENEM & TUNCAY 2024). The aforementioned publications show a clear shift in the focus of research within landscape architecture: studies now go beyond experiments with artificial intelligence and are increasingly concerned with systematic evaluations of its capabilities. Research is thus increasingly focused on the optimization and control of AI models.

The analysis of bias in models shows how important it is to critically examine training processes and databases. Global diffusion models, usually trained on billions of images, produce rather generic images that lack the characteristics of a specific location or specific style (KUDLESS 2023). With the help of latent diffusion models developed by ROMBACH et al. (2022) for example, users can optimise AI-models themselves by incorporating their own curated data. Today, up-to-date finetuning methods such as LoRA and DreamBooth, developed by Google researchers (RUOZ et al. 2022), allow to finetune global models such as Stable Diffusion, which has been trained on approximately 5 billion images, to a custom purpose and with a significantly lower number of images.

Studies by HUANG & LI (2024) and the design study on bridge aesthetics by ZHANG et al. (2024) demonstrate that models can be enhanced through the use of proprietary image data and text files or by integrating specific knowledge, such as expert knowledge from the fields of ecology and landscape systems as well as design knowledge. COOP Himmelb(l)au claim in their Instagram account that the “Deep Himmelblau Diffusion Node generative AI Model for Architectural Design outperforms its counterparts Midjourney, Stable Diffusion, and Dalle2 in text2image generation by outputting architectural semantics aligned with Coop Himmelb(l)au’s distinctive formal language” (COOP HIMMELB(L)AU 2025).

Although generative AI models have been widely optimised and controlled, only a few approaches exist in landscape architecture using image-generating AI, highlighting the need for a domain-specific methodological framework to adapt and control AI models in this context.

3 Methods

The research design systematically investigates the training of diffusion models in the context of landscape architecture, with a focus on incorporating the perspective of landscape architecture using fine-tuning techniques. The core objective is to explore the potential of personalised AI models in the early stages of the design process and, beyond that, to customise and implement these models in a practical manner. To achieve this, three distinct research questions are posed, each of which is investigated through targeted training tests and corresponding model evaluations.

The study explores AI models such as Stable Diffusion XL 1.0 using targeted fine-tuning (DreamBooth-Training / Low Rank Adaptation) to generate location-specific details, design-specific knowledge and characteristic graphic styles. To this end, three different training models were developed and tested: the location model, the concept control model and the look model.

Table 1: Research questions (I-III) to define the objectives for targeted model training

Framework	Research question	Resulting model
I. Site specificity	How accurately can a fine-tuned AI generate site-specific details?	I location model
II. Concept control	How can designers and AI work together to achieve truly novel design outcomes?	II concept control model
III. Look	Can the characteristic visual style (look) of a particular landscape architecture office be learned and regenerated by AI?	III look model

A mixed-methods approach is used, including training Stable Diffusion using pre-experiments and fine-tuning techniques LoRA and DreamBooth. The training process is divided into sequential phases, each reflecting different areas of application relevant to the early stages of landscape architecture (Table 1). The models were trained using specific data sets – adapted text-image pairs – from Heidelberg (I), best practice examples of social space quality and climate adaptation (II), and a specific landscape architecture firm (II/III). The training environment included powerful hardware (RTX 4090 GPU, 64 GB RAM) and software (Kohya_ss GUI/ DreamBooth Extension).

1) Location model (DreamBooth): Clear evaluation criteria are specified for the evaluation of the model to assess the identity-defining characteristics. Twenty images are created for each concept and evaluated on a five-point scale for each typology. A comparative non-parametric analysis (Mann-Whitney U test) is then performed with the same number of images using the base model (SDXL 1.0).

2) Concept control model (DreamBooth): trained on text-image pairs with integrated additional knowledge of places and then interacts with the location model (I) using an additional model merge. Quantitative analysis is limited due to its exploratory nature. Instead, input and output are compared based on specific criteria: image composition, integration of additional knowledge using captions and querying them during image generation (social place quality, infrastructure, climate adaptation). This approach helps to determine whether the model has acquired design knowledge.

   Look model (LoRA): trained on 50 text-image pairs of visualisations. HSL analysis is used in the third training test to quantify the similarity of the generated images to the original style and to gain insights into the efficiency of the training. The images are analysed distinguishing the hue, saturation and lightness (HSL) components to compare their styles. However, other methods such as colour analysis (comparison of RGB values) or texture analysis (examination of patterns and surface details) could also be used in future research. The choice of HSL analysis is therefore not exclusive, but representative of various possible approaches to eval uating and optimising style transfer models.

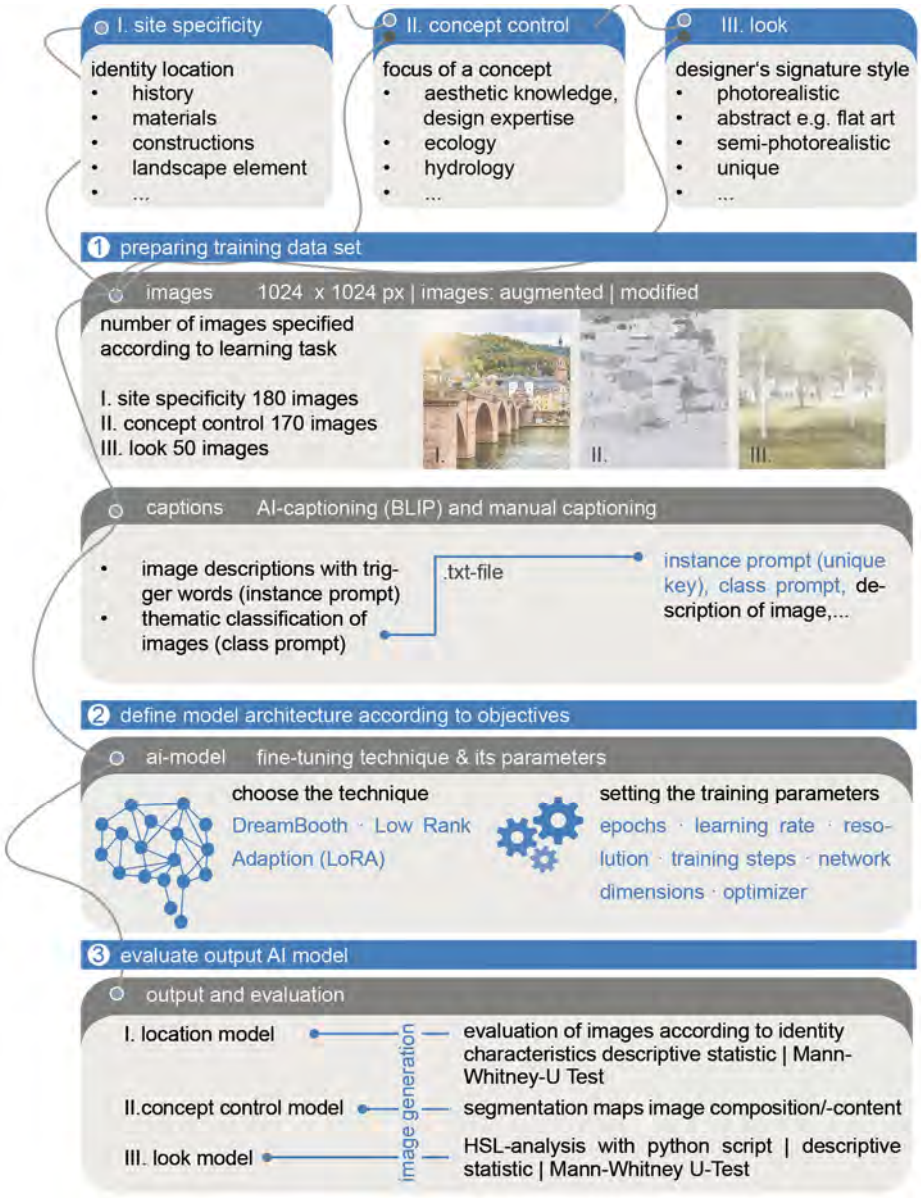

Fig. 1: Methodical training framework for AI training

4 Results

The work demonstrates that generative AI models can learn and regenerate specific expertise, thematic focuses, and graphic styles through targeted fine-tuning. The results highlight the potential of personalised AI for landscape architecture, particularly in the design phase, and open new possibilities for collaboration between humans and AI.

I. Location model: The aim was to create a realistic representation of location-specific details based on a dataset of 180 images from Heidelberg from four identical typologies – architecture (Castle), landscape-integrated elements (Old Bridge), town square (Bismarckplatz), city centre (Old Town). The trained model performed significantly better across three of four typologies (Old Bridge, Castle, and Bismarckplatz) than the base model (Table 2).

Table 2: Quantitative evaluation of the location model

Typology	AI model	Mean	Std. dev.	Median	iqr
Old Bridge	AI trained	2.85	0.93	3	1.75
	Base modell	0.7	0.8	0.5	1
Old Town	AI trained	3.75	0.44	4	0.75
	Base modell	3.4	0.5	3	1
Castle	AI trained	3.45	1.05	4	0.75
	Base modell	1.5	0.61	2	1
Bismarckplatz	AI trained	2.7	0.47	3	1
	Base modell	1.25	0.44	1	0.75

II. Concept control model: The aim was to integrate design-specific knowledge and thematic focal points such as social-place quality, climate adaptation and integrated infrastructure. The model was trained with 170 images and additionally combined with the previously trained location model. The results (Figure 3) show a fusion of location and concept information, which indicate a possible interaction between user and AI.

To analyse how far the fine-tuned model was improved through the curated images from the fine-tuning, input images (left column) were compared to output images (right column) through segmentation and content analysis. Figure 4 is showing the analysis for the prompt “spacious, social place quality, climate adaption”.

Fig. 2: Location model: ltr: Old Bridge, Old Town, Castle, Bismarck Square – top: basic model (SDXL 1.0) – row below AI trained

Fig. 3: Result of combining trained models I (location model) and II (concept control model)

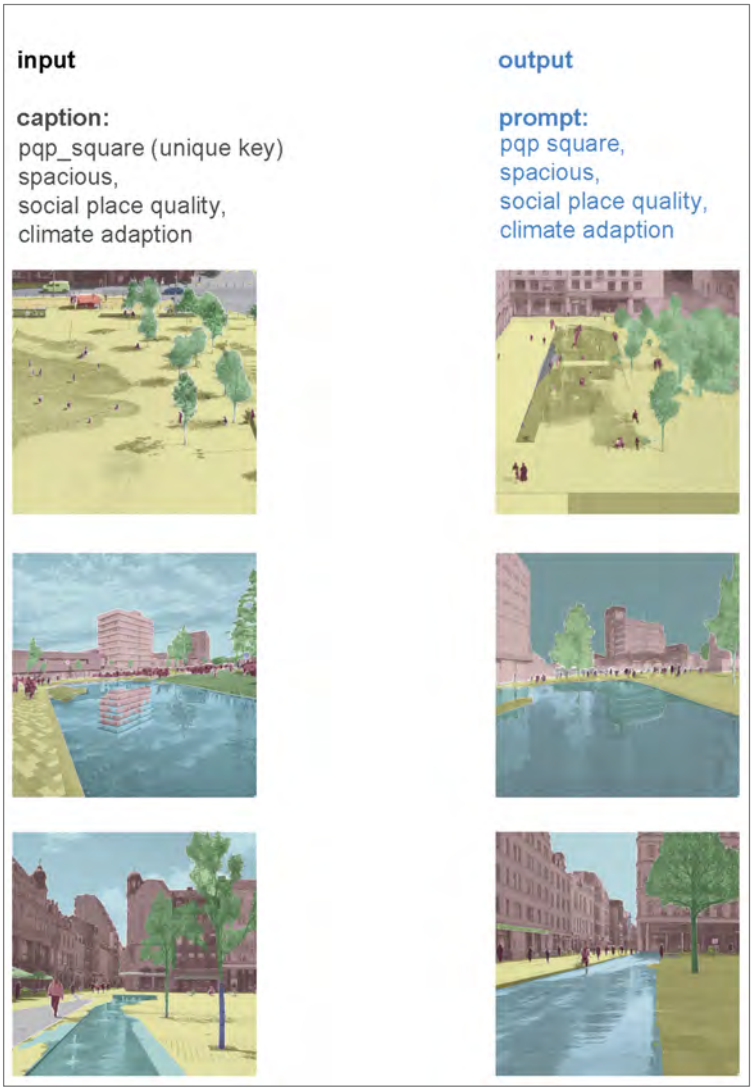

Fig. 4: Concept control model: Qualitative analysis of image content and successful training using segmentation maps

III. Look model: The aim was to learn and reproduce a specific graphic style with a clear focus on efficiency and stylistic accuracy. The model was trained using 50 images, all of which feature a hybrid, sketch-like style, and processed sequentially in several steps. To evaluate the success of the style transfer and training process, an HSL analysis (Fig. 5) was performed. This HSL analysis was carried out using a Python script generated and modified with ChatGPT (OpenAI 2024; ChatGPT (Version GPT-4o) [Large language model]. https://chat.openai.com/). The results showed that after three stages (epoch III), the model came closest to the input style, while a fourth stage (epoch IV) did not bring any significant further improvement.

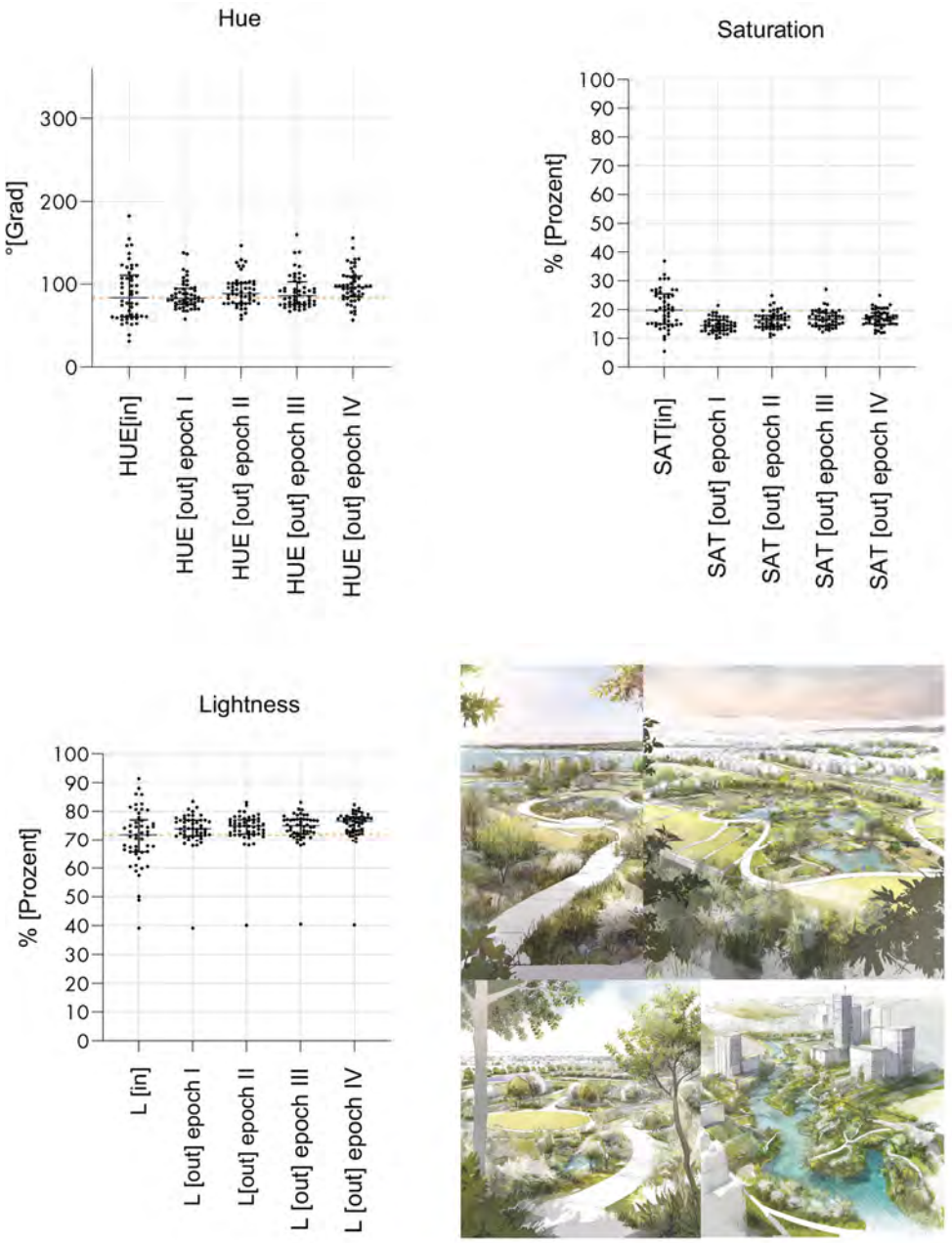

Fig. 5: **L**ook model: HSL analysis, bottom right: results look model (LoRA)

5 Discussion

5.1 Site-Specificity – Precision of Location-specific Generation

How accurately can a fine-tuned AI generate site-specific details?

The results show that finely tuned models can reliably capture location-specific features, although performance depends heavily on data quality and spatial complexity. For example, characteristic open space types, architectural objects and landscape elements in Heidelberg's city centre could be convincingly reproduced. The challenges included capturing complex spatial perspectives and avoiding misinterpretations. Bismarckplatz in particular proved to be a very complex learning task due to its small-scale, multi-layered and at the same time highly distinctive spatial structure, which led to comparatively lower evaluation results. Data preparation was made even more difficult by the limited availability of images and the need to remove distracting elements. In this case, DreamBooth training was used so that the model could learn the entire spatial composition of the location. A prepared training matrix made it possible to teach various spatial concepts in a targeted manner. The model shows clear learning performance: individual objects and perspectives can be addressed directly using specific trigger words, such as characteristic spatial objects. Particularly noteworthy is the training using the example of the castle, where heterogeneous structural design was successfully learned and is reflected in realistic results in image generation.

The work shows that such approaches can be transferred to other forms of location specific knowledge. It is also conceivable to integrate historical structures based on archive images, location-specific textures such as materials, or even self-made sketches from site visits. Such data sets could further support location-based, AI-assisted analysis and design.

5.2 Controlling the Concept – Humans and AI in the Design Process

How can designers and AI work together to achieve truly novel design outcomes?

The results show that guided interaction between human expertise and AI can lead to novel design outcomes. The findings demonstrate that targeted annotation and the combination of different models can integrate individual design knowledge into AI. Conscious control via prompts and training data unlocks creative potential and enables the development of innovative design variants. This approach also offers potential for participatory design processes and integration into education.

Instead of reproducing existing content, the focus was on the generative ability of AI systems to create new design proposals. These results continue to be based on the underlying design concepts and input data. In an additional experiment, concept and location models were combined to explore how different sources of knowledge and design authorship can be brought together. Both AI training and prompting proved to be iterative processes that required important design decisions on the part of the user, including the definition of goals, the degree of influence, and the selection and structuring of training data.

The training focused on spatial representations, especially photographs, as the AI models' prior knowledge in this area is significantly better developed than in abstract forms of representation such as site plans. Captions proved to be essential for embedding expert knowledge

into the model. Through fine-tuning, expert knowledge, office-specific preferences and design principles can be specifically utilised using image and text material, thereby achieving a controllable result.

The approach therefore enables designers to generate new insights, ideas and design impulses based on their own text-image data sets. This allows for controlled image generation, the communication of design values and the development of independent design approaches. As a result, the role of the designer is transformed from that of a user to an active co-creator of generative processes.

5.3 Look – Transferability of Stylistic Features

Can the characteristic visual style (look) of a particular landscape architecture office be learned and regenerated by AI?

The results show that stylistic features can be reliably learned and transferred if the training data is consistent and well structured. The Look model has demonstrated that consistent style transfer is possible with stylistically homogeneous training data and carefully optimised parameters. However, excessive deviations or excessive detail in the descriptions can compromise the results. Targeted adaptation of the training data set and the use of suitable model architectures proved to be key factors for successful style adaptation.

The applied HSL analysis provides an initial method for evaluating stylistic consistency but does not fully capture the graphic style. Even a limited number of training cycles proved sufficient to achieve resource-efficient results. Future work should include additional evaluation metrics such as texture features or RGB values and focus on clearly defined stylistic training tasks. Combining a style model (LoRA) with ControlNet proved to be an effective approach for achieving consistent stylistic results in different locations. ControlNet provides contextual control by incorporating spatial information. This ensures spatial coherence while maintaining a distinctive visual style.

6 Conclusion and Recommendations

This study demonstrates that diffusion models can be systematically controlled and optimised along three stages – location, concept control and look – enabling the generation of site-specific and stylistic coherent design outputs aligned with their design goals.

Finely tuned AI models can directly support landscape architects in generating location specific designs while meeting both aesthetic and stylistic requirements in practical workflows. Methodically precise preparation of the training data and active, iterative control of the AI training process by the users are essential for success. Precise goal definition and division into smaller, clearly defined training units are particularly important for complex, context-dependent tasks. The integration of expert knowledge and iterative user participation in the training process enable personalised AI solutions, demonstrating how landscape architects can tailor models to their specific de-sign needs, providing them tangible tools for site-specific-tasks. The qualitatively and quantitatively evaluated results show that AI models can reliably learn and reproduce both location-specific features and self-introduced graphic styles from their own curated datasets. In particular, the ability to incorporate expert knowledge

with the help of sample images and technical descriptions, as well as advantages in terms of data protection and competitiveness, open up new perspectives for design and planning in landscape architecture.

As their understanding of the technology grows, landscape architects can train their own customised models to better reflect specific requirements and increase competitiveness. Future research should focus more on how industry-specific knowledge can be integrated into AI models. It also remains to be seen how site plans and other complex formats can be reliably created by AI through targeted training and larger data sets, and how the interaction between image generators and other software should be designed so that designs can be efficiently integrated into workflows.

This study focused on image generators and the underlying diffusion models. Nevertheless, georeferenced work remains a central aspect of landscape architecture practice. Current diffusion models generate raster graphics and rely on comparable data sets. However, the pure diffusion model does not offer a comprehensive solution for location-specific contexts using geodata but requires the integration of additional AI models with different network architectures and the development of suitable interfaces to incorporate and link spatial information in a location-specific manner. The development of an entire workflow and the implementation of diffusion models in established software solutions with spatial reference, such as CAD programmes or GIS systems, may offer another opportunity to develop personalised models and make them accessible to a wider range of users.

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Use of LLMs

The following large language models were used only for language improvement purposes: ChatGPT (OpenAI, San Francisco, CA, USA); DeepL (DeepL SE, Cologne, Germany); Microsoft Copilot (Microsoft Corporation, Redmond, WA, USA).

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Fields of Probability: GeoAI-Based Plant Selection in Landscape Architecture

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Abstract: This paper examines how probabilistic species distribution modelling using Maximum Entropy (MaxEnt), implemented within a geospatial artificial intelligence (GeoAI)-based workflow, can be employed as a design support tool within landscape architectural practice in semi-arid environments. Applied within the context of a giga-scale development project in Saudi Arabia, the approach supported early-stage plant selection. Using concatenated botanical survey records, 28 plant species were modelled against a suite of 15 abiotic environmental variables following data cleaning, minimum occurrence thresholds (≥10 records), multicollinearity screening using variance inflation factors, and expert-led verification. The resulting outputs generated continuous, species-specific probability surfaces that revealed regional patterns of environmental association. The paper argues that while GeoAI-based workflows using MaxEnt offer valuable insights into regional environmental patterns, they systematically underrepresent biotic interactions and facilitation processes that govern species establishment within designed landscapes. Accordingly, model outputs are most effective when positioned as provisional design instruments within iterative digital landscape architecture workflows that integrate GeoAI-enabled modelling with field observation and design judgement, rather than being treated as predictive ecological truths.

Keywords: Maximum entropy, GeoAI, species distribution modelling, situated epistemology, plant selection

1 Introduction

This study investigates how a geospatial artificial intelligence (GeoAI) workflow can be integrated into landscape architectural practice within a development project in Tabuk Province, Saudi Arabia, using probabilistic species distribution outputs as spatial instruments to support early-stage plant selection. It argues that the limits of GeoAI workflows are not only technical but epistemic, reflecting a species-level mode of knowledge that captures regional patterns of environmental association while excluding the interaction-driven facilitation processes that shape plant establishment. In doing so, the study positions probabilistic modelling both as a design instrument and as an object of critical reflection, interrogating what forms of ecological knowledge are produced and excluded when ecology is reduced to data.

Maximum entropy (MaxEnt) species distribution models, implemented within a GeoAI workflow, are presence-only modelling approaches that estimate the spatial distribution of a target species by identifying a probability distribution of maximum entropy constrained by observed occurrences and selected environmental variables (PHILLIPS et al. 2006). The method is widely used in ecology because it can produce continuous suitability surfaces, or what we refer to as maps in landscape architecture, from presence-only data and because its mathematical formulation allows transparent statistical interpretation. Here, GeoAI refers to the integration of probabilistic modelling, spatial data infrastructures, and automated GIS workflows, rather than autonomous or deep-learning-based artificial intelligence. One example of this modelling approach applied as a plant selection tool is the web-based platform

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*Which Plant Where (*TABASSUM et al. 2023), which was developed to support evidence-based plant selection across varying climate scenarios.

In this context, MaxEnt models indicate where a plant species is most likely to occur across the site based on patterns observed in botanical field surveys and similarities in environmental conditions. These outputs are frequently interpreted as guidance for plant selection, often implicitly assuming that predicted suitability corresponds to conditions for establishment. In this paper, *fields of probability* refer to spatialised representations of likelihood derived from statistical associations between species occurrences and environmental variables, used to support design judgement rather than to predict ecological outcomes. These fields are constructed rather than discovered.

From the outset, the purpose of applying the model was not to prescribe a definitive planting palette, but to identify *fields of probability* that could inform early-stage design exploration, guide plant selection, and align environmental planning with both ecological and commercial objectives. This approach was adopted for the following reasons:

1) **Limited availability of botanical field survey data,** which constrained the analysis to presence-only records without systematically recorded absences.
2) **Capacity to generate continuous spatial suitability surfaces,** here referred to as maps, which integrate multiple abiotic environmental factors and spatial criteria, enabling visualisation of species-level distribution patterns across the site.
3) **Compatibility with GIS-based design workflows,** allowing model outputs to be automated, exported, and iteratively refined by designers and planners to improve long-term planting strategies based on site observations and ground-truthing.

2 Fields of Probability

2.1 Occurrence Records and Environmental Variables

All models were implemented in ArcGIS Pro (v3.1) using a GeoAI-enabled spatial workflow with a MaxEnt backend. Model training employed a fixed random seed (seed = 42) to ensure reproducibility. A botanical field survey commissioned for this project and conducted by an external specialist team in March 2023 provided the empirical basis for model development (AL-GILANI et al. 2023). Survey locations were established by identifying high-priority 20 m x 20 m quadrats across the study site, informed by Normalised Difference Vegetation Index patterns derived from Sentinel-2 imagery at 10 m resolution acquired on 17 October 2022, as well as site accessibility considerations to support field access and survey implementation. A total of 145 species belonging to 130 families were recorded during the survey. From this dataset, 28 species with at least 10 recorded occurrences were identified and included in the modelling process, consistent with commonly adopted thresholds for presence-only modelling (ABDELAAL et al. 2019). Species with fewer occurrences were excluded from automated model runs.

Environmental variables were selected based on their relevance to species distribution processes (ADHIKARI et al. 2012). A total of 15 abiotic predictors informed the MaxEnt models: precipitation, wind exposure, valley depth, topographic wetness index, slope, aspect, elevation, land-cover, local habitat descriptor, geological bedrock type, soil type, vegetation class, distance to wadi, mean annual temperature, and solar isolation.

The habitat layer, for example, comprises a mapped classification of the study area into eight discrete habitat classes with a minimum mapping unit of 1 hectare: alluvial plains; coastal and inland sabkhas; well-drained coastal plains; Midian slopes; oases, farmland and plantations; rocky terrain of the Hisma Plateau; sand sheets and dunes; and wadis and drainage channels. All environmental layers were resampled to a common spatial resolution of 20 m (Table 1).

Table 1: Environmental variables that affect species distribution

Variable	Significance	Format	Source Resolution
Valley Depth Index	Deeper valleys may enhance water retention and drainage, influencing suitability for cultivation	GeoTiff	10 m
Topographic Wetness Index	High values indicate wetter areas and increased water availability	GeoTiff	10 m
Topographic Roughness Index	Smoother terrain may help cultivation activities and rougher terrains could pose challenges	GeoTiff	10 m
Sun Duration Hours	Influences growth and development of plants	GeoTiff	10 m
Slope	Affects water runoff, erosion, and ease of cultivation	GeoTiff	10 m
Aspect	Influences sunlight exposure and affects temperature and moisture condition for cultivation	GeoTiff	10 m
Altitude	Influences temperature, atmospheric pressure and oxygen levels that affect plant life	GeoTiff	10 m
Average Rainfall	Crucial for plant growth	GeoTiff	30 m
Vegetation Index for Winter	Existence and density of vegetation during Winter	GeoTiff	15 m
Vegetation Index for Summer	Existence and density of vegetation during Summer	GeoTiff	15 m
Habitats	Spatially explicit representation of ecological variation across the study area, based on eight clearly defined habitat classes	GeoTiff	20 m
Land Surface Temperature	Influences plant growth and development, in relation to heat stress or cold intolerance	GeoTiff	30 m
Geological Bedrock Type	Influences nutrient availability and drainage conditions	SHP	-
Flood	Indicates risk of flooding that can have significant impact on the feasibility of cultivation and choice of species	Grid	10 m
Distance to wadis	Proximity to dry riverbeds and may show potential water source or risk associated with flooding during heavy rainfall period	GeoTiff	10 m

2.2 Removal of Correlations between Variables

Once the data were cleaned and organised according to the occurrence threshold, and all environmental variables were resampled to a common spatial resolution, we screened for multicollinearity using the Variance Inflation Factor (VIF). Multicollinearity occurs when two or more independent variables in a model are highly correlated, making it difficult to distinguish their individual effects on the response variable – in this case, species occurrence. VIF quantifies the extent to which the variance of an estimated regression coefficient is increased due to such correlation (LIAO & VALLIANT 2012). VIF was applied to assess the severity of multicollinearity among predictors, using a conservative exclusion threshold of VIF > 5. This screening resulted in the removal of three to five variables per species (mean = 3.8 variables) from the initial predictor set. For example, sun duration and land surface temperature are commonly correlated, as areas with greater daily solar exposure often experience higher temperature. The most frequently correlated variable pairs included solar duration versus land surface temperature, and elevation versus mean annual temperature (Figure 1). Consequently, one of these variables within the pair may be excluded to reduce bias. By retaining only weakly correlated environmental variables, we improved model interpretability and reduced the risk of overfitting.

2.3 Distribution Model using Maximum Entropy

The fundamental principle for presence-only MaxEnt modelling in species distribution analysis is to estimate the probability distribution of a species *close to uniform* (maximum entropy), while being constrained by environmental variables observed at known species occurrence locations (YI et al. 2016). The model begins with the assumption that a plant species is equally likely to occur anywhere across the landscape. This assumption is then iteratively refined using the observed environmental characteristics associated with surveyed occurrence points. As a result, the output maps identify areas that share similar environmental conditions to observed locations as having higher relative suitability for the species to occur. This model is typically adopted for species distribution modelling as it is particularly well-suited for scenarios where only presence data is available (YANG et al. 2013). Based on limited botanical survey data from the region, this model allows us to infer *potential locations* for where particular species can be located based on limited but informative environmental inputs (PHILLIPS et al. 2006). This is particularly useful in this region because it:

1) **Captures non-linear relationships** between environmental variables and species distribution through flexible feature functions, enabling the model to represent complex ecological responses to environmental gradients and anticipated anthropogenic land-use change pressures associated with development (e. g., infrastructure expansion, terrain modification, altered drainage connectivity, and localised microclimate effects).
2) **Suits data-scarce contexts,** performing effectively with presence-only records where absence data are unavailable or unreliable, which is common in remote semi-arid landscapes.
3) **Handles high-dimensional environmental datasets** through regularisation, allowing multiple climatic, topographic, and environmental variables to be considered simultaneously without overfitting.
4) **Supports expert-informed workflows** where supplementary datasets, variable selection, bias correction, and post-model interpretation can incorporate domain knowledge to improve ecological plausibility and decision relevance.

The model can be expressed mathematically using the following equation (PHILLIPS et al. 2006):

$$P(x) = \frac{1}{Z} exp\left(\sum_{i=1}^{n} \lambda_i f_i(x)\right)$$

$P(x)$ is the relative probability (or probability density) of species presence at location *x*.
Z is a normalisation constant that ensures the probability distribution sums to 1 across the study area (or background space).
λ_i are Lagrange multipliers associated with constraints derived from the observed presence data.
f_i (x) are feature functions representing transformations of the environmental variables at location *x*.

The sum in the exponent represents a linear combination of the feature functions. During model training, the objective is to determine the values of λ_i that maximise entropy subject to the standard MaxEnt constraints derived from the presence data (feature expectation matching) and regularisation; no additional external spatial constraints (e. g., exclusion masks or rule-based constraints) were applied in this analysis.

Following model execution, species-specific hyperparameter tuning and internal testing were applied only where occurrence sample sizes were sufficient to support stable estimation; for smaller sample sizes, conservative/default regularisation settings were retained to reduce instability and overfitting risk. MaxEnt typically incorporates a regularisation term that penalises overly complex models and reduces the likelihood of fitting noise in the data. Once the model is trained and optimal values of λ_i are determined, the resulting probability distribution $P(x)$ can be used to predict the relative suitability of different locations for each species. In the absence of background (absence) data, MaxEnt includes a bias correction term to account for potential sampling bias in the presence-only datasets.

Model performance was evaluated using multiple metrics, including the area under the receiver operating characteristic curve (AUC-ROC), true positive rate, and false positive rate (ADHIKARI et al. 2012). Twenty per cent of the occurrence records were reserved for model validation. Following validation, AUC-ROC values exceeding 0.85 were considered indicative of excellent predictive performance for plant distribution mapping. Across all species, validation AUC-ROC values ranged from 0.78 to 0.93, with a mean AUC of 0.87 (±0.04 SD). In addition, continuous Boyce Index values ranged from 0.61 to 0.89, indicating good model calibration. Mean omission rates at the 10th percentile threshold were ≤12% for 23 of the 28 modelled species. Expert verification was subsequently applied as an additional plausibility check prior to map export.

To illustrate the outcomes of the modelling approach, one of the 28 surveyed species is presented as an exemplar. Figure 1 shows the response curves and coefficients for *Haloxylon salicornicum*, indicating that climate and topographic variables, particularly rainfall, wind exposure, valley depth, and topographic wetness, were dominant predictors for this species. The exported map illustrates continuous probability surfaces that were used as decision-support tools for plant selection within the design process (Figure 2).

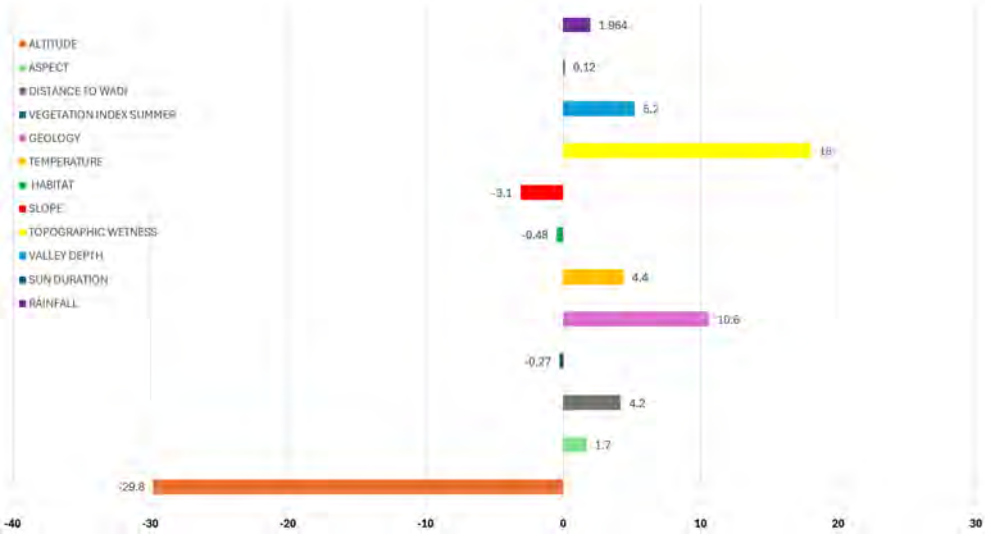

Fig. 1: MaxEnt coefficient and response curves for *Haloxylon salicornicum.* Of the initial 15 environmental variables, 12 were kept following multicollinearity screening.

Coefficient signs indicate the direction of association with the fitted model score conditional on other predictors; for habitat classes, coefficients do not imply an ordinal ranking of habitats and are not interpreted as pre-defined suitability ordering.

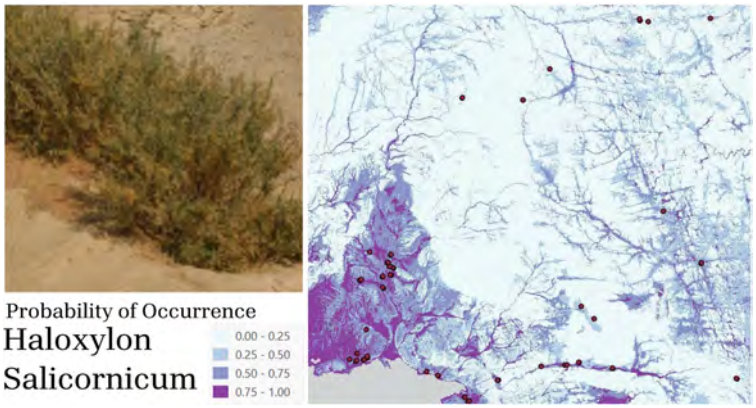

Fig. 2: Modelled probability of occurrence for *Haloxylon salicornicum.* Occurrence points on maps are based on botanical survey records and were used as presence data.

3 Discussion

Throughout the project, we emphasised that MaxEnt primarily captures statistical relationships between species occurrences and environmental predictors such as climate, topography, and edaphic variables. As a result, biotic interactions and localised stressors are underrepresented unless explicitly included as model predictors. This limitation informed the use of the resulting maps as decision-support artefacts to guide field validation and early design scenarios, rather than as conclusive ecological truths. In this sense, MaxEnt provides a partial view of site ecology – one of pattern and correlation rather than process and coexistence. This reveals a fundamental epistemic tension between what is measurable and situated ecological reality. The knowledge produced by GeoAI-enabled workflows is therefore epistemologically situated, shaped by methodological choices, data availability, and assumptions about relevant environmental information. An additional limitation arises from treating species as independent modelling units, which excludes facilitation mechanisms and other dependency structures that organise plant assemblages and influence ecological outcomes.

Although the probabilistic models were initially developed to guide planting palettes through reasonably accurate predictions of species distributions, this use quickly exposed the inadequacy of treating statistical suitability as a proxy for plant establishment outcomes. Landscape persistence is sustained through reciprocal and context-dependent biotic interactions that exceed the representational capacity of MaxEnt models. Field observations indicate that plant establishment is strongly shaped by facilitative biotic interactions. For example, within the coastal desert zone, shade from *Acacia tortilis* (al-Samar) moderates thermal stress and moisture loss, enabling understory establishment under otherwise harsh conditions; while salt-tolerant shrubs such as *Haloxylon salicornicum,* observed within the same survey quadrats, stabilise saline substrates and buffer microclimatic extremes for less tolerant species. These nurse-plant interactions are driven by proximity, canopy structure, and soil modification, yet are systematically underrepresented by MaxEnt models, despite often determining whether a planting system persists or collapses. As a result, such models tend to privilege ecological correlation over ecological relation. Model outputs describe where plants might occur, but only partially capture how planting systems are assembled, supported, and sustained through interdependent site processes.

Rather than rejecting GeoAI-based MaxEnt models, this paper argues for their repositioning within plant selection workflows. *Fields of probability* can operate as an initial spatial filter, but meaningful plant selection ultimately depends on integrating model outputs with site conditions, biotic interactions, and landscape design intent to avoid deterministic interpretations of suitability, particularly in semi-arid environments shaped by both abiotic stress and biotic cooperation among species.

4 Conclusion and Outlook

From this study, we draw three key conclusions. First, probabilistic outputs require careful scaling and interpretation; in this context, regional patterns are more informative than species-level specificity for early-stage design decision-making. Second, abiotic correlation should not be conflated with ecological causation, and biotic interaction must be deliberately reintroduced through iterative design and field engagement. Third, effective design integra-

tion depends on an iterative process in which modelling, observation, and critical reflection co-evolve throughout project development.

Across the modelled species, validation performance at the study-area extent was generally strong, indicating reliable regional-scale discrimination; however, fine-grained site-level probability patterns and boundary delineations varied by species and were more sensitive to parameterisation choices and occurrence sparsity. This contrast reinforces the appropriateness of probabilistic modelling for strategic, early-stage planning rather than fine-grained ecological prescription.

While GeoAI-enabled MaxEnt workflows provide actionable spatial insights into the environmental drivers of species distributions, their reliance on physical variables underrepresents biotic interactions and context-specific stressors, particularly in urban and semi-arid environments. Such abstraction can lead to significant design oversights. The task of the designer is not to displace ecological judgement with modelling, but to reassert relational intelligence by treating *fields of probability* as speculative surfaces for dialogue rather than deterministic prescriptions.

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AI Landscape Design Studio and the Future of Digital Creativity in Landscape Architecture

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Abstract: Artificial Intelligence (AI) is reshaping creative workflows in landscape architecture, offering powerful tools for analysis, ideation, and visualization. This paper examines an AI-assisted landscape design studio conducted at the Faculty of Sciences, University of Porto (FCUP) as a pedagogical case study to explore AI's role as a creative partner in design. It integrates literature on AI-driven creativity, the shifting role of the designer from author to editor, impacts on design education and practice, and ethical and ecological considerations. The studio methodology combined traditional site analysis with AI tools (ChatGPT for program generation, MidJourney/DALL·E for concept visualization, and AI-powered software for design refinement), enabling students to rapidly iterate and refine landscape proposals. Results indicate that AI can augment creativity and efficiency – expanding the range of ideas and enhancing visual communication – while simultaneously challenging students to apply critical judgment and uphold ethical standards. The paper discusses benefits (enhanced ideation, improved workflows) alongside challenges (de-skilling risks, authorship and bias concerns), reflecting on how such AI-integrated studios provide a lens into the future of digital creativity in landscape architecture. The findings suggest that AI, when thoughtfully integrated, can empower landscape architects as co-creators rather than replacements, and call for evolving educational frameworks to prepare designers for this emerging paradigm.

Keywords: AI in landscape architecture, design studio pedagogy; human-AI co-creation, designer as curator

1 Introduction

The emergence of AI in design is heralding a transformative era for landscape architecture, offering novel methodologies to address urgent challenges like climate change and sustainability. Recent advances in machine learning – from generative image models to conversational AI – enable designers to analyze complex environmental data, generate imaginative design concepts, and produce high-quality visualizations with unprecedented speed. Rather than viewing AI as a threat, an increasing number of practitioners see it as a powerful ally that augments human creativity and efficiency. As one industry observer noted, AI is being used as "a tool to enhance the creative process in landscape design… offering new ways to conceptualize and refine design ideas," expanding what designers can achieve. Crucially, this augmentation does not supplant the landscape architect's role; even advanced generative models remain "a long way from… the capability to design an entire [project]" on their own, as Yale's Phillip Bernstein cautions. Instead, AI's value lies in amplifying human ingenuity – offloading routine tasks to intelligent systems so that designers can focus on higher-level creative decision-making.

Within this context, the ***AI Landscape Design Studio*** at FCUP was conceived as a pedagogical experiment to investigate AI's potential as a collaborative design partner in landscape architecture. Conducted in the *Information Technologies in Landscape Planning and Design* course in 2024, this studio challenged students to integrate AI tools at every stage of their

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design process. The intent was twofold: (1) to leverage AI in crafting regenerative landscape solutions for real-world sites, exploring new creative workflows, and (2) to critically reflect on how AI is changing the role of the designer, design education, and professional practice. By documenting this experiment, the study aims to shed light on the benefits and pitfalls of incorporating AI into landscape architecture studios, and how it might shape the future of digital creativity in the field.

This paper is structured as follows. The ***Literature Review*** discusses key themes on AI as a creative partner, the evolving role of the designer (from sole author to curator/editor), impacts on design workflows and education, and known benefits and challenges of AI integration – including ethical, ecological, and pedagogical considerations. The ***Methodology*** section then details the design of the AI Landscape Design Studio and its AI-enhanced workflow, from site analysis to visualization. The ***Results*** section presents insights from the studio experiment, illustrating how students used AI tools, what outcomes were achieved, and reflections from the process. In the ***Discussion***, these findings are interpreted in light of the literature – examining how the studio confirms or nuances existing views on AI in design and what this implies for future practice and teaching. Finally, the ***Conclusion*** distills the main lessons and outlines future directions, positing how AI can be harnessed to create more informed, imaginative, and responsible landscape architecture in the years ahead.

2 Literature Review

Across architecture and landscape architecture, AI is increasingly framed not as an autonomous designer but as a *creative partner* working alongside human designers. This paradigm shifts the designer's role from sole author to collaborator and curator. Rather than producing finished designs independently, AI systems contribute ideas, analyses, and imagery that must be evaluated, selected, and refined by the human designer. In this way, AI expands the cognitive "search space" of design, while human judgment remains central to ensuring contextual relevance, quality, and value alignment.

Generative design algorithms and large language models exemplify this collaborative dynamic by producing multiple alternatives from defined parameters or prompts, thereby supporting early-stage ideation and reducing fixation on initial solutions. Studies consistently indicate that AI-assisted ideation increases the novelty and diversity of concepts considered. However, AI does not determine design outcomes: professional judgment is required to interpret and adapt outputs to project goals, site conditions, and ethical considerations. When used appropriately, AI functions as a co-creator that amplifies human creativity rather than replacing it – a perspective consistent with broader architectural discourse that positions AI as assistive rather than autonomous.

Research has begun to explore AI participation in early design generation. Basarir and Erol (2021), for example, demonstrate how AI can generate architectural concept sketches from textual briefs, illustrating AI's capacity to contribute from the outset of the creative process. Nevertheless, the value of such systems depends on the designer's ability to frame problems clearly and critically evaluate outputs. Co-creative design studies consistently emphasize that meaning-making, problem framing, and solution recognition remain fundamentally human responsibilities. AI is therefore best understood as an extension of the designer's imagination, offering inspiration and efficiency while relying on human direction and contextual understanding.

As AI increasingly generates preliminary analyses and imagery, the designer's role is shifting toward that of curator or editor of content. Designers now spend more time guiding algorithms – through prompt formulation or parameter tuning – and critically refining AI outputs, rather than manually producing every design element. This shift requires new competencies, particularly in communicating design intent to AI systems and interpreting outputs that are often incomplete or biased.

Bernstein argues that designers must "take advantage of AI innovation without being supplanted by it," emphasizing the need to steer AI tools rather than allow them to dictate outcomes. In practice, human-AI interaction resembles a dialogical process in which designers request alternatives, AI generates possibilities, and designers exercise editorial judgment. Iterative prompt refinement becomes analogous to iterative sketching, with authorship emerging through continuous human-machine exchange.

At the same time, scholars warn against over-reliance on AI. Ackerman (as cited by MORTICE 2024) cautions that overly "push-button" tools risk reducing design to a purely curatorial activity, potentially eroding disciplinary depth. The emerging consensus highlights the need for dual competencies: strong foundational design skills combined with fluency in AI-assisted workflows. Design education must therefore incorporate AI literacy, including awareness of algorithmic limitations, biases, and tendencies such as hallucinated outputs. Overall, the designer's role is evolving from sole creator to editor-in-chief of AI-generated content, combining traditional design judgment with algorithmic guidance.

AI integration is already reshaping landscape architecture workflows. Early adopters report significant efficiency gains in site analysis, option generation, and visualization. AI systems excel at processing large datasets and automating repetitive analyses, enabling more evidence-based design decisions. In conceptual design, AI's ability to generate multiple alternatives with minimal effort supports more iterative and exploratory workflows, allowing designers to test scenarios rapidly and compare solutions.

AI has also had a pronounced impact on visualization and communication. Text-to-image tools such as DALL·E and MidJourney can generate atmospheric concept imagery from simple verbal descriptions, dramatically reducing production time. These images primarily function as discussion tools, facilitating comparison of alternatives and communication with stakeholders. The designer's role remains one of curation and refinement, ensuring that AI-generated visuals align with site conditions, cultural context, and design intent. As Li and Amoroso note, AI-generated visualizations often require human adjustment, underscoring that AI streamlines workflows without eliminating the need for human oversight.

The literature identifies key benefits of AI integration in landscape architecture, including increased efficiency, expanded creative exploration, improved data-informed decision-making, and enhanced visual communication. In educational contexts, AI can lower representational barriers for less-experienced students, enabling greater focus on design thinking. AI has also been positioned as a potential support for sustainable and regenerative design through rapid environmental simulation.

However, challenges remain significant. De-skilling is a central concern if designers rely excessively on AI for foundational tasks. Quality control is critical, as AI-generated content may include inaccuracies or ecological inconsistencies. As Fayyad (2023) notes, effective AI use depends on human oversight and data curation. Ethical and legal issues – particularly regarding authorship, intellectual property, and embedded bias – also persist. Consequently,

the literature frames AI neither as a solution nor a threat, but as a disruptive technology requiring deliberate governance. As Koehler (2023) argues, designers must actively shape AI outputs, leveraging generative capacity while preserving intentional human authorship and core values of ecology, community, and creativity.

3 Methodology: Studio Design and AI-Enhanced Workflow

The AI Landscape Design Studio was conducted as a semester-long project within a master's-level landscape architecture course. Sixteen students worked in teams of four, each selecting a 1-hectare site requiring regenerative landscape interventions, in alignment with the course theme *"Regenerative Landscapes: Designing the Transition."* The pedagogical approach combined conventional landscape analysis and design methods with AI-based tools, establishing a hybrid, AI-enhanced workflow. The process was structured into sequential phases, with AI integrated throughout.

First, teams undertook ***site selection and data collection*** using traditional methods, including field surveys, photographic documentation, and the analysis of climatic, topographic, soil, and land-use data. In some cases, mobility datasets (e. g. Strava) were used to understand spatial use patterns. This phase ensured that all projects were grounded in real-world environmental and spatial conditions prior to AI use.

Second, teams engaged in ***program generation using ChatGPT (GPT-4)***. Based on site data and observed challenges, students conducted iterative dialogues with the AI to develop project programs and design objectives. ChatGPT functioned as a "thinking partner," supporting brainstorming and the identification of potential programmatic elements and precedents. AI-generated suggestions were critically assessed and selectively incorporated, resulting in a written design brief co-developed through human-AI interaction.

Third, ***concept exploration*** was carried out using AI image-generation tools, primarily MidJourney (v5) and DALL·E 3. Students crafted and iteratively refined text prompts to generate concept images, mood boards, and speculative visualizations. Multiple generators were used comparatively, allowing teams to explore diverse spatial atmospheres and design directions. AI outputs were curated rather than adopted directly, serving as visual stimuli for design development.

Fourth, teams progressed to ***design development and AI refinement***, combining conventional CAD, GIS, and 3D modeling tools (AutoCAD, QGIS, SketchUp) with AI-assisted visualization. AI was used to enhance site photographs and model views through generative image editing and AI-driven rendering plugins (e. g. diffusion-based rendering). This mixed workflow allowed rapid visualization while maintaining human control over spatial accuracy, ecological appropriateness, and design intent.

Finally, in the ***synthesis and presentation phase***, students integrated analytical drawings, AI-assisted visuals, and written narratives into coherent design proposals. AI-generated material was explicitly annotated and contrasted with refined outputs to clarify the role of AI versus human decision-making. Deliverables included master plans, sections, perspectives, and a narrative report. The studio concluded with a published booklet documenting projects, workflows, and reflective commentary, supported by a round-table discussion evaluating the benefits and limitations of AI tools.

Throughout the studio, students maintained ***AI interaction logs***, documenting prompts, iterations, and decision-making processes. These logs functioned as reflective journals and supported both pedagogical assessment and critical discussion. Ethical considerations and AI limitations were addressed explicitly through critiques focused on bias, realism, and contextual validity. Faculty acted as facilitators within an iterative learning environment, with the methodology understood as adaptive and evolving alongside advances in AI technologies.

3.1 Data Collection and Analysis

Data sources for this study comprised: (1) AI interaction logs maintained by each of the four student teams throughout the semester, each containing prompts, iterative revisions, and rationales for accepting or rejecting AI outputs; (2) written design briefs and reflective statements submitted at the end of each phase; (3) structured critique notes recorded by faculty during mid-semester review; (4) jury feedback collected at the final presentation; and (5) grading rubric scores assessing conceptual depth, design resolution, visual communication, and critical reflection. Student work and reflections were used anonymously, with participation in the documentation process agreed upon at the outset of the course.

Fig. 1: AI-generated conceptual landscape visualization produced during early design exploration. Original image generated by students using a text-to-image AI model based on a project-specific design prompt for a climate-adaptive urban park in Porto. The image was used as an ideation and discussion tool, supporting exploratory thinking rather than representing a finalized design proposal.

Analysis followed an interpretive, qualitative case study approach (FRANCIS 2001, YIN 2003). Interaction logs were coded thematically, with recurring categories including: prompt iteration patterns, incidence of AI output rejection or significant human editing, and types of failure modes encountered (e. g. spatial inaccuracies, culturally inappropriate imagery, hallucinated program elements). Two faculty members independently coded a shared subset of logs to reduce interpretive bias, resolving disagreements through discussion. Descriptive in-

dicators – such as average prompt iterations per phase (range: 4-12 per team per phase) and the proportion of AI-generated images ultimately rejected or substantially edited (approximately 60-70% across teams) – are used to illustrate findings where relevant. These figures are indicative rather than statistically generalizable, given the small cohort size.

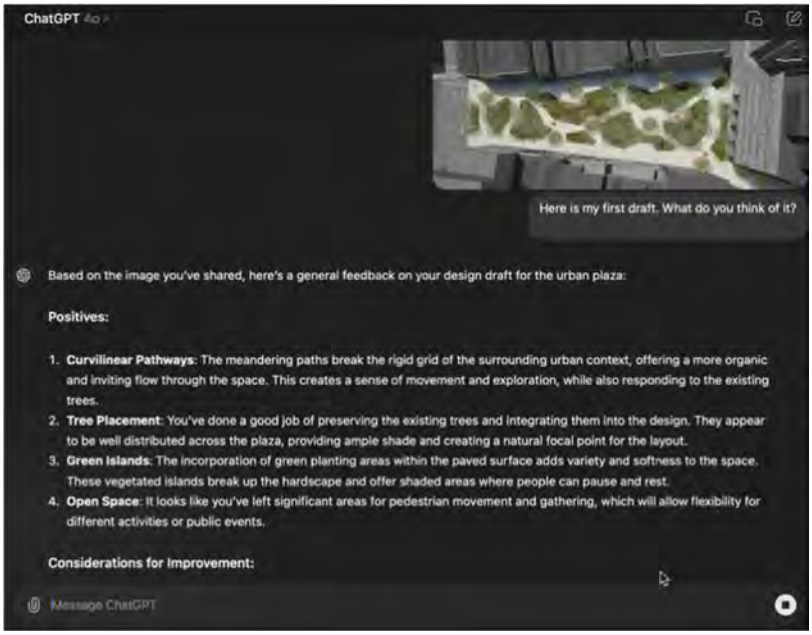

Fig. 2: Exemplifies the dialogical use of conversational AI, where students critically evaluated and selectively integrated AI-generated feedback

Fig. 3: AI-assisted refinement of student landscape visualization. Comparison between an initial student-produced render (top) and an AI-refined visualization (bottom). The refined image demonstrates enhanced lighting, materiality, planting composition, atmospheric conditions, and representation of human presence, while remaining guided by the designer's intent and site-specific context.

Figures 1-3 document key moments of the AI-enhanced design workflow developed in the studio, illustrating generative ideation, human-AI dialogue, and AI-assisted visual refinement. These figures support the interpretation of results discussed in the following section.

4 Results and Findings

The AI Landscape Design Studio produced a diverse set of student projects and generated clear insights into collaborative human-AI design processes. Overall, the results show that AI tools significantly increased the speed, breadth, and iterative capacity of landscape design exploration, while reinforcing the central role of human judgment, critical reflection, and pedagogical guidance.

A primary impact of AI integration was the expansion of ideation during early design phases. Using MidJourney and DALL·E, students rapidly generated multiple visual alternatives, enabling broader exploration of spatial strategies and atmospheres than would typically be feasible within the same timeframe. Students reported that AI-generated imagery often triggered unexpected associations and supported creative synthesis across different design directions. Compared to previous non-AI studios, the range of concepts explored per project was noticeably wider, suggesting that AI-supported visualization can reduce early design fixation and encourage exploratory thinking, consistent with findings reported in the literature (e. g. JIN et al. 2023).

AI integration accelerated iterative design processes by allowing students to test modifications through prompt adjustment rather than redrawing or remodeling entire schemes. Teams iterated more frequently than in conventional workflows, enabling earlier visual evaluation of design decisions. Time savings were particularly evident in visualization tasks, freeing students to focus on analysis, refinement, and critique. However, instructors also observed a key risk: the ease of producing polished AI images occasionally led to premature design closure, requiring pedagogical intervention to reinforce that visual quality does not equate to design rigor.

Final project outcomes were strong both visually and analytically. Faculty reviewers noted that presentation quality matched or exceeded that of previous cohorts, with AI-assisted renderings effectively communicating atmosphere, materiality, and design intent. These visuals were supported by coherent design logic and evidence-informed reasoning. At the same time, variations in AI-generated imagery required additional post-processing and manual editing, reinforcing the lesson that AI outputs function as raw material and that visual coherence remains a fundamentally human responsibility.

Student reflections indicate that AI tools were largely experienced as empowering, particularly in overcoming representational barriers and supporting exploratory thinking. Participants developed new skills in prompt formulation, iterative refinement, and critical evaluation of AI outputs, alongside a clearer understanding of authorship and responsibility. Initial concerns about AI as “cheating” gave way to recognition that AI amplifies, rather than replaces, design judgment. From an instructional perspective, AI integration required a shift toward facilitation and ethical moderation, with strategic non-AI checkpoints proving essential to foreground core design reasoning.

5 Discussion

The AI Landscape Design Studio offers a concise view of how artificial intelligence may shape landscape architecture education and practice. Overall, the results reinforce current literature framing AI as a *creative partner* rather than an autonomous designer, while clarifying the conditions under which its benefits are realized and its risks amplified.

A central finding is that AI functions effectively as a co-creator but cannot replace the design process. Students consistently had to guide, interpret, and correct AI outputs, supporting Bernstein's claim that AI remains "a long way from… the capability to design an entire project on their own." Outputs were fragmentary and required human synthesis to achieve coherence and contextual relevance. When used critically, unexpected AI results prompted students to clarify design intent, strengthening reflective reasoning, as also noted by Birkeland (2024). However, this benefit depended on active engagement; without it, AI risked enabling superficial design.

The studio confirmed the shift from designer-as-author to designer-as-curator/editor. Students who excelled developed skills in prompt formulation and output selection, highlighting the growing importance of AI literacy alongside traditional design competencies. Encounters with biased imagery and language-model inaccuracies underscored the need for designers to understand AI limitations at a conceptual level. This suggests an emerging hybrid role for landscape architects, combining design expertise with data and tool awareness.

AI integration accelerated ideation and visualization, enabling more iterative and non-linear workflows consistent with reported productivity gains. However, the apparent completeness of AI-generated images sometimes encouraged premature design closure. Faculty intervention was necessary to reinforce that visual polish does not equate to design rigor, echoing earlier experiences with CAD and digital rendering tools. Disciplined critique and iterative testing remain essential.

The studio validated key benefits identified in the literature – expanded ideation, faster communication, and partial support for evidence-informed reasoning – while revealing clear limits. AI imagery proved effective for discussion and engagement but risked overstating design resolution, requiring transparency. Similarly, AI-supported analysis did not replace site-specific research or local knowledge. Challenges related to de-skilling, bias, and authorship were mitigated through manual checkpoints, culturally specific prompting, and explicit disclosure, reinforcing Mortice's argument that designers must curate AI outputs through human values.

Pedagogically, the findings support embedding AI within design studios, provided that ethics, reflection, and foundational skills remain explicit. For practice, the studio anticipates hybrid workflows in which AI absorbs routine tasks while designers focus on synthesis, feasibility, and value-based judgment. As AI tools become more accessible, the landscape architect's role as curator, facilitator, and translator of design intent may become even more central. Finally, the energy footprint of AI highlights the need to align digital innovation with sustainability goals.

Studio AI Policy

The following principles governed AI use in the studio and are offered as a replicable studio AI policy framework. (1) Disclosure and annotation: all AI-generated content was required

to be explicitly labelled in final submissions, distinguishing AI-generated from human-authored material. Students annotated which tools produced which outputs and at what stage of the process. (2) Authorship expectations: students were assessed on their curatorial and critical decisions – the selection, rejection, and transformation of AI outputs – rather than on AI-generated imagery per se. AI outputs were treated as raw material; final design authorship rested with the student. (3) Citation of AI use: AI tool names, model versions, and prompt contexts were recorded in the interaction logs and referenced in the written narrative, following emerging conventions for transparent AI citation (e. g. tool name, version, date, and prompt summary). (4) Non-AI checkpoints: three mandatory phases required entirely non-AI deliverables: the initial site survey and hand-drawn analysis, the conceptual parti diagram, and the final hand-annotated master plan. These checkpoints ensured that core design reasoning and spatial thinking skills were demonstrably exercised and assessed independently of AI augmentation.

Overall, the findings confirm that AI, when integrated thoughtfully, can enrich landscape architecture education by expanding creative exploration, accelerating iteration, and enhancing communication. Human creativity, contextual understanding, and critical judgment remain indispensable, with the most successful outcomes emerging from a deliberately human-directed, AI-assisted design process. [Paragraph relocated from Results section.]

Overall, the studio points toward a hybrid future for digital creativity in landscape architecture – one in which AI contributes speed and variation, while human designers retain responsibility for vision, meaning, and holistic judgment.

6 Conclusion

The AI Landscape Design Studio at FCUP demonstrates that artificial intelligence can significantly enhance creativity, efficiency, and exploratory capacity in landscape architecture when used as a *creative partner* rather than an autonomous designer. AI-supported workflows expanded ideation, accelerated visualization, and supported iterative design, while reinforcing the central role of human judgment in guiding, curating, and contextualizing outcomes.

Successful integration depended on designers' ability to direct AI tools, evaluate outputs critically, and embed ecological and cultural meaning. These demands highlight the need for dual competencies – design thinking and AI literacy – and underline the growing importance of the studio AI policy framework described in Section 5.

Pedagogically, the experiment suggests that AI can be integrated into landscape architecture education as a standard design tool, provided that reflective practice, ethical awareness, and foundational skills remain explicit. Looking ahead, AI-assisted workflows are likely to reshape professional practice by increasing iteration speed and expanding creative exploration, while reaffirming the landscape architect's responsibility for vision, judgment, and human-centered design.

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AI Ethics, Frameworks and Data Analysis

The Influence Mechanism of Innovation Output in Resource-Based Cities from the Perspective of Eco-City: A Method Based on an Explainable Machine Learning Model

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Abstract: Landscape environment plays a significant role in the innovation development of resource-based cities. From the perspective of eco-city, this study selects 23 regenerated resource-based cities in China as the research area and builds an interpretable machine learning method to uncover how service facilities, social economy, and the landscape environment relate to urban innovation output. Firstly, a reasonable factor framework was constructed. Secondly, the influencing factors were screened and models were compared. Thirdly, the contribution degree of factors was analysed using SHAP. Fourthly, the interaction effect of factors was analysed using PDP. This study reveals that science and education venues exert a significant positive effect on the innovation output of regenerated resource-based cities. High-quality landscape environments can effectively stimulate the innovation vitality of these venues. Explainable machine learning method can incorporate the landscape environment into the urban research framework, revealing the relationships between the landscape environment and various urban features. Through the interpretation of the results, targeted development suggestions can be provided for the city, which has strong practical guiding significance.

Keywords: Resource-based cities, eXtreme Gradient Boosting, Shapley Additive exPlanations, innovation output

1 Introduction

This is a descriptive paper of a complex process. Here, we present an explainable machine learning analysis method to reveal the mechanism between multiple influencing factors and urban innovation output. This method can incorporate multiple landscape environmental features into the urban research framework and analyse their synergy with other urban features.

Resource-based cities are those cities whose main development model is the exploitation and processing of natural resources. The single model driven by resource extraction has led to economic, social and environmental problems such as resource depletion and imbalanced industrial structure (FAN 2024). In 2013, China promulgated the Sustainable Development Plan of National Resource-based Cities, 2013-2023, classifying resource-based cities into four categories: growth, maturity, decline, and regeneration. Among them, the regenerated resource-based cities, as the forefront of innovative transformation among resource-based cities, have significant reference value for other cities in their pursuit of sustainable development (ZHENG et al. 2020). We select all the regenerated resource-based cities in China as the research subjects.

The current research on urban innovation development lacks explanations for the complex influencing mechanism. Most studies classify the driving factors of innovation development from one or two dimensions, but the understanding of how these factors affect each other and

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their interrelationships is very limited. The landscape environment, as an important dimension of urban innovation development, is rarely taken into comprehensive consideration (ZHANG et al. 2023, ZHOU et al. 2025). Therefore, it is necessary to start from an overall perspective and construct a holistic framework to explore the influencing mechanism of multiple features to provide guidance for urban innovation development.

The concept of eco-city was initially proposed to address issues of industrial pollution and environmental deterioration. The introduction of the "ecological" concept from natural ecology emphasizes the need to conduct the overall design of cities from an ecological perspective to achieve harmonious development of society, economy and nature (CHEN et al. 2025). Currently, it's a key strategy for the development of resource-based cities.

To unravel the influence mechanism between urban innovation output and diverse factors, traditional quantitative models such as social network analysis, the super efficiency DEA model, and ordinary least squares analysis have been widely employed. However, it's difficult for these models to handle the nonlinear relationships that occur in real situations. Machine learning models offer an effective alternative for analyzing complex urban innovation. However, their application in research is limited by interpretability challenges. Explainable artificial intelligence, such as Shapley Additive exPlanations (SHAP), visualizes the influence mechanisms and can reveal the interrelationships between different factors.

Thus, this paper introduces an interpretable machine learning model. Among them, the Extreme Gradient Boosting (XGBoost)makes accurate predictions based on gradient boosting trees. SHAP model, based on the Shapley value in game theory, explains the importance of each factor. Partial Dependence Plots (PDP) describes the specific impact of individual or multiple factors on the model results. The interpretable machine learning model can deeply explain the influence mechanism of multiple factors, which is helpful for improving urban governance capabilities.

Here we provide a brief description of the interpretable machine learning method, emphasizing the roles of each step and the brief explanations of the diagrams. Through this work, we have reached three key conclusions.

1) The interpretable machine learning method, which integrates machine learning models, SHAP and PDP, can effectively analyse the nonlinear and interactive effects of multiple factors on urban innovation development, breaking through the limitations of traditional linear regression methods.

2) Explainable machine learning method can incorporate the landscape environment into the urban research framework, revealing the relationships between the landscape environment and various urban features. Through the interpretation of the results, targeted development suggestions can be provided for the city, which has strong practical guiding significance.

3) Science and education venues have a strong promoting effect on the innovation output of regenerated resource-based cities. High-quality landscape environments can effectively stimulate the innovation vitality of these venues.

2 A Method Based on an Explainable Machine Learning Model

2.1 Frame Construction

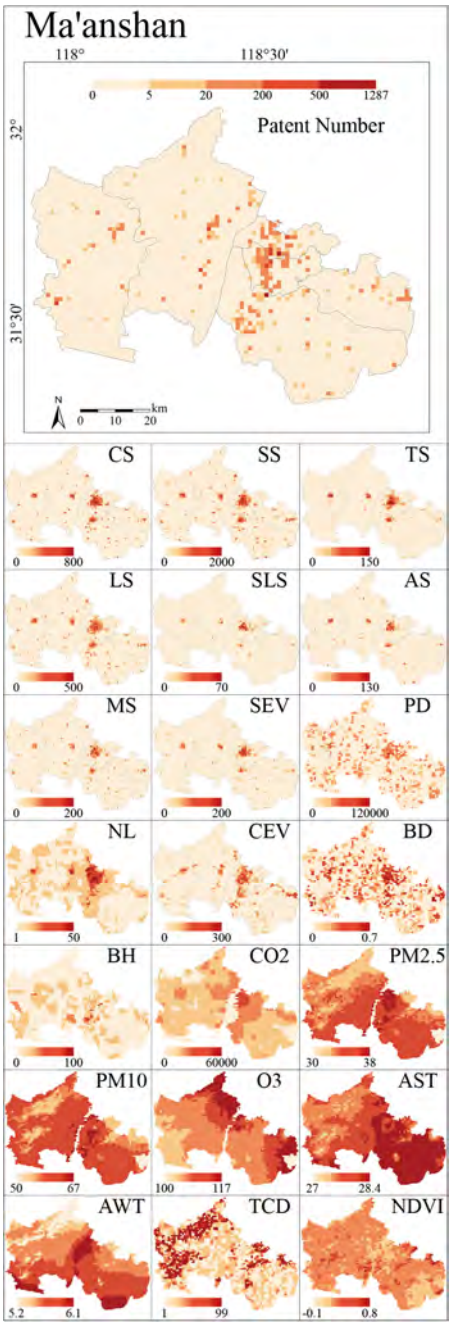

Fig. 1:
The spatial distribution of factors in Ma'anshan in 2023

The theory of eco-city emphasizes that cities are complex ecosystems integrating social, economic and natural elements. Its core lies in guiding the organization of urban space based on ecological principles. Landscape architecture focuses on the form and function of green spaces, emphasizing the improvement of urban environmental quality through systematic ecological design. In the process of innovative transformation of resource-based cities, they face dual challenges of ecological restoration and urban renewal, and need to coordinate and optimize the synergy of functional services, social economy and ecological environment. Therefore, this study, based on the theoretical connotations of eco-city and landscape architecture, has constructed a framework of three dimensions: service, society and environment. The service dimension focuses on public service facilities that provide diverse resources for innovation. The social dimension focuses on the development level of urban areas. The environmental dimension focuses on the ecological benefits of resource-based cities. Good air quality, comfortable climate, and high greenery quality can enhance the happiness and innovation ability of talents. The interactivity of these three dimensions can provide references for landscape architecture design.

2.2 Data Resource

Patent data is widely utilized by scholars for research on innovation in urban areas. Many researchers believe that although patent data cannot fully reflect all aspects of innovation, it remains one of the most direct, effective, and quantifiable indicators. The number of patents is generally regarded as an ideal quantitative indicator for measuring the innovation capacity of a region. Meanwhile, 21 factors related to urban innovation output were selected based on the literature and shown in Table 1. The service dimension includes catering, shopping, transportation, living, leisure, medical care, accommodation facilities. The social dimension includes population density, night light intensity, companies, building height and building density. The environmental dimension includes CO2, PM2.5, PM10, O3, summer average temperature, winter average temperature, tree coverage rate and normalized difference vegetation index (NDVI). The time range of the data in this study is 2013, 2018 and 2023. Spatial units are divided into grids of 1km by 1km. A 1km grid can precisely reflect the internal spatial characteristics and evolution patterns of a city at a micro scale and has been widely adopted in existing research. The 1km by 1km grid roughly corresponds to the blocks enclosed by main roads and is often regarded as a relatively complete urban spatial unit in terms of function. Research conclusions at this scale can be well applied to planning and construction practice. Due to page limitation, we have taken Ma'anshan City as an example to illustrate the spatial distribution of each factor in 2023 (Fig. 1).

Patent data are sourced from the China National Intellectual Property Administration. The night light intensity, NDVI and temperature data are obtained from National Earth System Science Data Center. The tree cover data are derived from the China Annual Tree Cover Dataset. POI data are chiefly derived from the Baidu Maps Open Platform. Air quality data are obtained from the China High Air Pollutants. The building density and population data are derived from the Global Human Settlement Layer, and the population data are corrected with census data. The carbon mission data are obtained from the Open-Data Inventory for Anthropogenic Carbon dioxide. The building height data are derived from the CMTBH-30 dataset.

Table 1: Description of multidimensional influencing factors

Dimensions	Factors	Description
Service dimension	CS	The number of catering facilities (units/km²)
	SS	The number of shopping facilities (units/km²)
	TS	The number of transportation facilities (units/km²)
	LS	The number of living facilities (units/km²)
	SLS	The number of sports and leisure facilities (units/km²)
	MS	The number of medical facilities (units/km²)
	AS	The number of accommodation facilities (units/km²)
Social dimension	PD	Number of resident population (persons/km²)
	NL	Nighttime light intensity (nWcm-2 sr-1/km²)
	CEV	Number of companies and enterprises (units/km²)
	BD	Building density (%)
	BH	Average building height (m)
	SEV	The number of science and education venues (units/km²)
Environmental dimension	CO2	Monthly fossil fuel carbon dioxide emissions (tons/km²)
	PM2.5	Annual average PM2.5 concentration (μg/m³)
	PM10	Annual average PM10 concentration (μg/m³)
	O3	Annual average O3 concentration (ppb)
	AST	Average summer temperature (°C)
	AWT	Average winter temperature (°C)
	TCD	Tree cover degree (%)
	NDVI	Normalized Difference Vegetation Index

2.3 Factors Selection and Models Comparison

Highly correlated different factors often undermine the accuracy of the model and are usually regarded as redundant factors. The Pearson correlation coefficient is a statistical indicator for measuring the correlation between two variables and can be used for the preliminary screening of factors (Fig. 2). Notably, the correlations of CS, SS, LS, MS, and CEV all exceed 0.85. CS and LS belong to daily consumption facilities and have overlapping layouts with most service facilities. The VIF values of CS and LS are higher than 10, and in the initial analysis using machine learning, their SHAP values were found to be relatively low. In contrast, the istribution overlap of SS, MS, and SEV is relatively low, with VIF values less than 5 and higher SHAP values. Therefore, the two factors of CS and LS were excluded. As shown in Table 2, the VIF values of the remaining 19 factors are all less than 5, indicating that there is no multicollinearity in the model.

To demonstrate the applicability of XGBoost in this study, a total of 5 machine learning models and 2 traditional models were selected for comparative analysis. The machine learning models were Random Forest (RF), Adaptive Boosting (Adaboost), Extreme Gradient Boosting (XGBoost), Support Vector Regression (SVR), and Gradient Boosting Decision Tree (GBDT). The traditional models were Ordinary Least Squares (OLS) and Negative Binomial Regression (NB). For the machine learning model, 5-fold cross-validation is adopted to optimize the hyperparameters, reduce noise and enhance the generalization ability of the

model. XGBoost outperforms other models with remarkable superiority and wide applicability. Compared to the linear assumption limitations of OLS, it can accurately capture the complex nonlinear relationships between variables, which is in line with the complex urban environment. Compared with SVR, it does not require cumbersome feature preprocessing and reduces the interference of outliers through regularization terms. Compared with random forests, it effectively suppresses overfitting through multiple mechanisms such as learning rate and regularization, and has better generalization performance. Compared with GBDT, with optimization techniques like parallel computing and sparse sensing, the training efficiency is significantly improved, and it is suitable for large scale data. Compared with NB, it has fewer restrictions on data types and distributions.

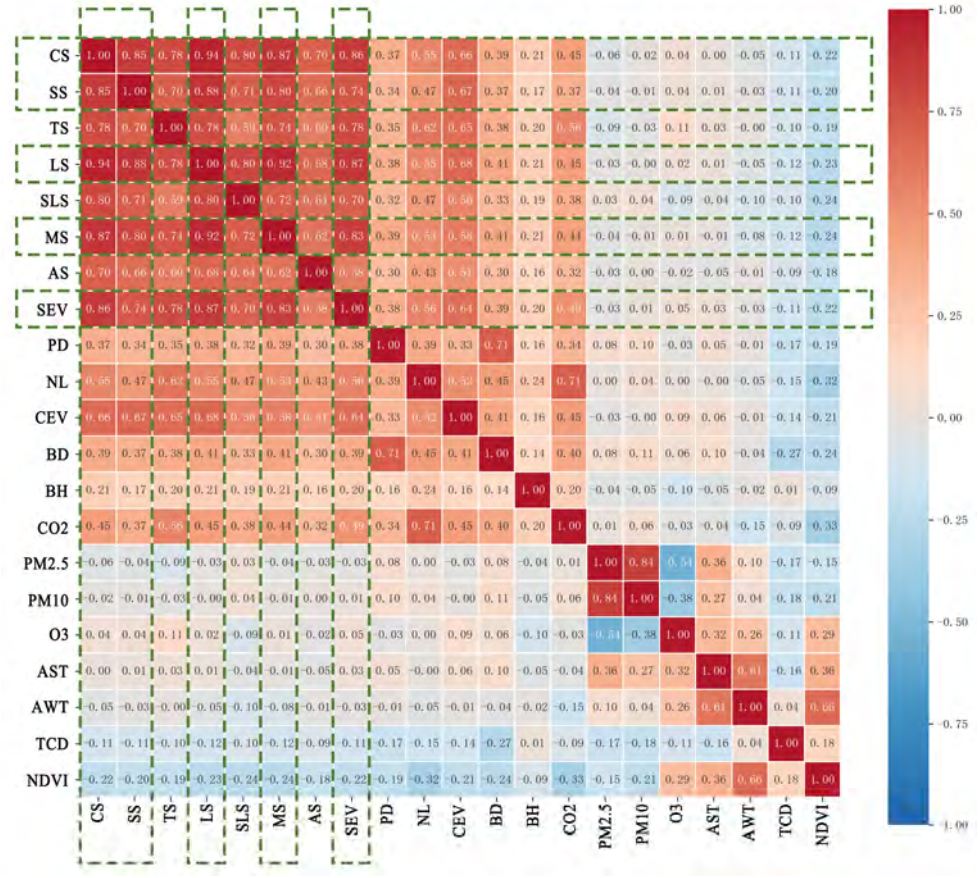

Fig. 2: Pearson correlation heat map of influencing factors

As shown in Table 3, the R^2 values of the prediction set and the test set of XGBoost are 0.6923 and 0.6165 respectively. The 40% variance of the test set might be attributed to data noise or spatial heterogeneity. This indicates that the XGBoost model has higher scientific validity when analysing this dataset.

Table 2: VIF result of factors

Factor	**SS**	**TS**	**SLS**	**MS**	**AS**	**SEV**		
VIF	3.89	3.71	2.78	4.81	2.14	4.48		
Factor	**PD**	**NL**	**CEV**	**BD**	**BH**			
VIF	2.13	2.64	2.31	2.41	1.12			
Factor	**CO2**	**PM2.5**	**PM10**	**O3**	**AST**	**AWT**	**TCD**	**NDVI**
VIF	2.27	4.88	3.93	3.07	3.04	2.66	1.21	2.41

Table 3: Result of models (XGBoost key params: max_depth=5, learning_rate=0.01, n_estimators=1500, subsample=0.8, colsample_bytree=0.8, gamma=0.1, reg_alpha=1, reg_lambda=2, min_child_weight=2, random_state=2)

Model	RF	Adaboost	**XGBoost**	SVR	GBDT	OLS	NB
Prediction set R^2	0.5694	0.5726	**0.6923**	0.4439	0.5165	0.1555	0.2227
Test set R^2	0.3868	0.4948	**0.6165**	0.4116	0.3396		

3 Results and Discussion

3.1 The Relative Importance of Factors Explained by SHAP

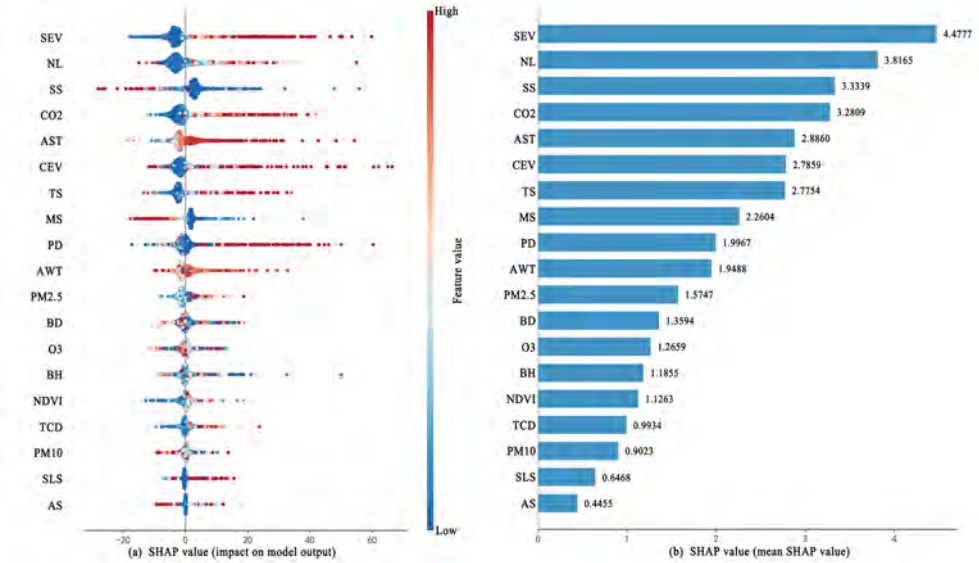

Fig. 3: Summary of relative importance of factors (SEV is Science and Education Venues)

To more accurately assess the influence degree of multiple factors, this study used the SHAP model to quantitatively rank the contribution degree of each factor (Fig. 3). In Figure 3a, the horizontal axis represents the SHAP value. Positive values indicate that the factor has a positive impact on the result, and the larger the value, the greater the contribution of the factor, and vice versa. Colours tending towards red indicate that the value of the factor is relatively high, while colours tending towards blue indicate that its value is relatively low.

As shown in Figure 3b, the relative importance of SEV is the highest (4.4777). The high value part is all greater than 0, and the low-value part is all less than 0. This indicates that the increase in urban science and education venues will lead to a significant increase in urban innovation output. Science and education venues provide a favourable cultural atmosphere and educational resources, attracting innovation spaces to settle in. Large meeting rooms offer venues for close communication among talents. Through cooperation among industry, academia, and research, the innovation output capacity is enhanced. For the environmental dimension, CO2 and AST are relatively more important. This might be because the materials for innovation activities in resource-based cities mainly consist of natural resources, which could lead to more CO2 pollution and high temperatures.

3.2 The Nonlinear Effect Based on PDP

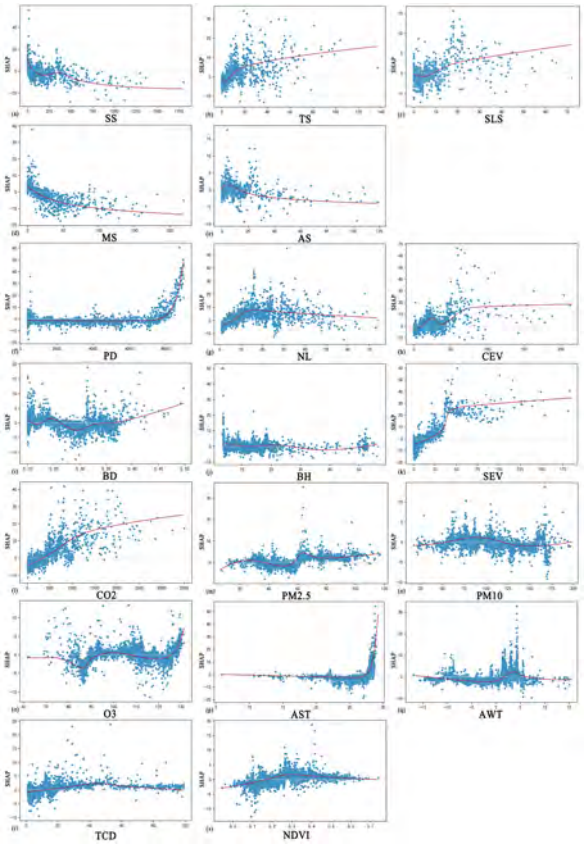

Fig. 4: The nonlinear effect of factors

This study further analysed the nonlinear relationship using the PDP model (Fig. 4). For SEV, the number of facilities ranging from 25 to 50 showed a significant increase in the promotion effect on innovation output, and then stabilized. This indicates that only when scientific and cultural facilities reach a certain degree of aggregation can they effectively promote regional

innovation capabilities, and beyond the threshold, the improvement effect on innovation capabilities is weak. The influence of environmental dimension elements on innovation output can be classified into three categories. The first category is CO2. As its value increases, the overall impact shifts from inhibition to promotion, and within a certain range, the promoting effect rapidly intensifies. However, after reaching a certain threshold, the promoting effect gradually levels off. This can be explained by the fact that the research and development objects in resource-based cities with regeneration mainly focus on natural resources, which generates a large amount of CO2. However, the innovation capacity along this path is limited. The second category includes O3 and AST. High values overlap with innovation activity clusters, indicating that innovation activities are related to air pollution and high temperatures. The third category consists of PM2.5, PM10, AWT, TCD, and NDVI. As their values increase, the promoting effect on innovation output strengthens. However, after reaching a certain threshold, the promoting effect gradually weakens. This suggests that high-quality greenery can stimulate innovation vitality, but excessive greenery may occupy research and development space, leading to a decline in innovation vitality.

3.3 Interaction Effect of Multidimensional Influencing Factors

To gain a more comprehensive understanding of the interactive effects among the three dimensions, this study employed the SHAP feature interaction analysis and presents the interaction effects of 19 features with their most strongly interacting factors (Fig. 5). The horizontal axis represents the value of the feature, the vertical axis represents the interaction SHAP value, and the colour represents the value of the interacting feature. For example, the SHAP value of AST for patent output is positive, but the SHAP value of the interaction between AST and CEV is negative. This indicates that the summer heat and company clustering will reduce the promoting effect of summer heat on patent output, rather than suggesting that the summer heat and company clustering will inhibit patent output.

For the environmental dimension, the interaction between CO2 and PD is the strongest, and the interaction SHAP value is always negative, indicating that population concentration inhibits the promoting effect of CO2 on innovation output. When the AST value is high, as CEV increases, the negative value of the interaction SHAP value increases, suggesting that high summer temperatures inhibit the innovation capacity of areas with concentrated companies. The SHAP interaction value between AWT and O3 changes from negative to positive as AWT increases, indicating that O3 has significantly different effects on regions with different winter temperatures. When the SEV value is high, the interaction SHAP value between NDVI and SEV is high and increases with the increase in NDVI, suggesting that in areas with concentrated science and education venues, a better landscape environment can effectively promote innovation output. Innovation activities constitute cognitively demanding labour, and high-quality green spaces serve as restorative environments that alleviate mental fatigue. Concurrently, high-quality green public spaces provide venues for informal interactions among innovative talents, thereby effectively amplifying the spatial agglomeration effects of science and education venues. Therefore, eco-city needs to attach great importance to the construction of high-quality landscape environment around science and education venues.

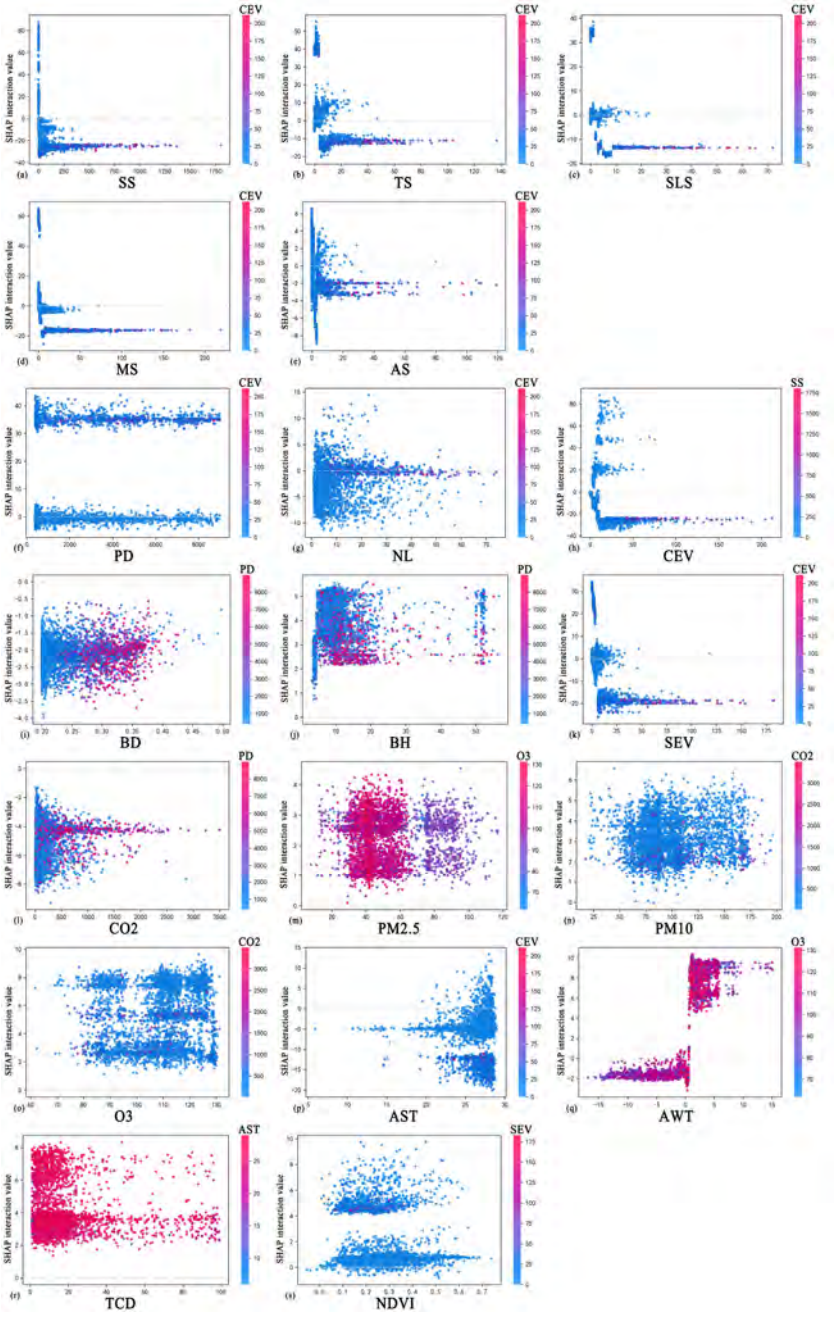

Fig. 5: The interaction effect of factors

4 Conclusion and Outlook

Landscape environment plays a significant role in the innovation development of resource-based cities. From the perspective of eco-city, this study selects 23 regenerated resource-based cities in China as the research area and builds an interpretable machine learning method to uncover how service facilities, social economy, and the landscape environment relate to urban innovation output. Firstly, a reasonable factor framework was constructed. Secondly, the influencing factors were screened and models were compared. Thirdly, the contribution degree of factors was analysed using SHAP. Fourthly, the interaction effect of factors was analysed using PDP.

Machine learning methods are being widely applied, but the relationship between the landscape environment and urban factors has not been given enough attention, and the interpretability is weak. We believe that interpretable machine learning methods should be used to analyse the role of the landscape environment in urban development. In summary, interpretable machine learning models can provide a unique perspective for landscape environment design and planning.

Although this study provides valuable method, it also has some limitations. Firstly, other features such as employment growth, R&D spending, and start-up formation could be incorporated into the innovation system. Secondly, innovation output has spatial autocorrelation, so local and global models could be constructed with using spatial weights to improve the accuracy of machine learning. Thirdly, due to paper constraints, we only briefly discussed the results. We will explore the reasons and propose suggestions in next paper.

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Integrating LLM Sentiment Analysis and SHAP Interpretability: Public Preference Assessment in Urban Parks

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Abstract: As effective nature-based solutions, urban parks play a critical role in design practice and environmental management, making it essential to understand how their landscape characteristics and surrounding environmental attributes influence public preferences. This study employed a large language model to conduct fine-grained, aspect-level preference analysis, revealing the nonlinear relationships between park and environmental features and public preferences, and highlighting the substantial potential of large language models for related research. The results indicate that park area and total edge exhibit positive threshold effects, with critical values of 22 ha and 30,000 m, respectively. Ample and well-connected blue–green spaces, high-quality vegetation cover, moderate morphological complexity (with an LSI threshold of 30) and appropriate facility provision, together with effective control of crowding and excessive hardscape development, play a crucial role in enhancing public preferences for and experiential quality of urban parks.

Keywords: LLM, urban parks, landscape preferences, machine learning models, ABSA

1 Introduction

High-intensity land development has continuously encroached upon natural spaces within cities, leading to substantial degradation of urban ecological environments and increasing scarcity of urban green resources. As a result, urban development is confronted with an acute tension between growing spatial demands and limited land supply. Against this backdrop, how to effectively enhance the provision of nature and ecological well-being within highly built-up environments has become a core issue that urgently needs to be addressed in the pursuit of urban sustainability. As a vital component of urban green infrastructure, urban parks – owing to their combined ecological and social functions – are widely regarded as effective nature-based solutions (LEMES DE OLIVEIRA 2025).

In the process of realizing the functions of urban parks, the public's subjective perceptions and evaluations of landscape environments play a crucial role. Landscape preference, as a psychological response grounded in aesthetic judgment, emerges through rapid cognitive processing and directly influences individuals' willingness to use parks as well as their emotional experiences. To systematically explain the mechanisms underlying preference formation, KAPLAN & KAPLAN (1989) developed the landscape preference matrix based on human needs for environmental information and its accessibility, proposing four dimensions – complexity, coherence, legibility, and mystery – which have provided a widely applicable theoretical foundation for research on environmental preference (LIU et al. 2025).

Existing studies indicate that a richness of natural elements can significantly enhance aesthetic preferences (WANG et al. 2019). Meanwhile, the spatial configuration of landscapes was directly associated with residents' visual preferences (DE VAL et al. 2006). The aggregation of blue–green spaces has been shown to make a notable contribution to promoting social

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cohesion and residents' well-being (WANG et al. 2023). Further empirical research revealed the nonlinear effects of landscape shape, edge density, and green space proportion on aesthetic perception and perceived safety (BI et al. 2024). In addition, public preferences were influenced by surrounding facility conditions and accessibility (LYU & ZHANG 2019). However, existing studies largely rely on two-dimensional planar indicators to characterize landscape features, which are insufficient to capture three-dimensional attributes such as vertical structure and visual perspective that may influence preferences. Therefore, systematically representing the multidimensional landscape characteristics of urban parks and their surrounding environmental attributes, as well as thoroughly elucidating their influence mechanisms on public preferences, is crucial for both design practice and environmental management.

The rapid development of big data and artificial intelligence has made social media data an important source for capturing the public's instantaneous perception of urban landscapes. The identification of opinions in unstructured text has advanced the field of sentiment analysis, which aims to extract structured information such as opinions, stances, and evaluations from text (LIU 2012). Among these methods, Aspect-Based Sentiment Analysis (ABSA), a fine-grained sentiment analysis technique, is designed to analyze public opinions regarding specific aspects (ZHANG et al. 2022). However, there is still a lack of dedicated models for assessing specific preference dimensions using social media data, and constructing tailored datasets to train deep learning models remains highly challenging. This process not only involves complex annotation schemes but also entails substantial time and resource costs. In recent years, large language models (LLMs), with their capabilities in instruction-following as well as few-shot and zero-shot learning, have provided a feasible approach for conducting fine-grained sentiment analysis under conditions of limited annotated data (SCARIA et al. 2023).

In summary, although LLMs have demonstrated immense potential in the field of text sentiment analysis, their application in the field of landscape architecture is still in its nascent stage, and how LLMs can be leveraged to interpret public landscape preferences is still unclear. Based on this, the present study employs a LLM to perform fine-grained ABSA for evaluating public landscape preferences toward urban parks. By quantifying both park and surrounding environmental characteristics using multi-source big data, this research further explores the non-linear relationships between these characteristics and public preferences. This study aims to explore and expand the diverse application patterns of LLMs in landscape preference research, with the expectation of providing new analytical tools and research perspectives for the field. The ultimate goal is to provide scientific support and a solid basis for decision-making to enhance the social and ecological co-benefits of urban green infrastructure systems, and to promote more precise and intelligent development of urban green spaces.

2 Data and Methods

This study focuses on the central urban area of Nanjing, Jiangsu Province, China. A total of 117 urban parks were selected as the study sites, each with an area larger than 0.4 ha and more than 20 social media posts, and their boundaries were manually verified using satellite imagery (Fig. 1). To comprehensively examine the potential factors influencing public preferences, two categories of variables were considered: internal park characteristics and sur rounding environmental attributes (Tab. 1). The selected indicators met the following criteria:

strong theoretical and practical relevance; perceptibility from the users' perspective; clear definitions; quantifiability; ease of acquisition; and broad recognition and application in existing research and practice.

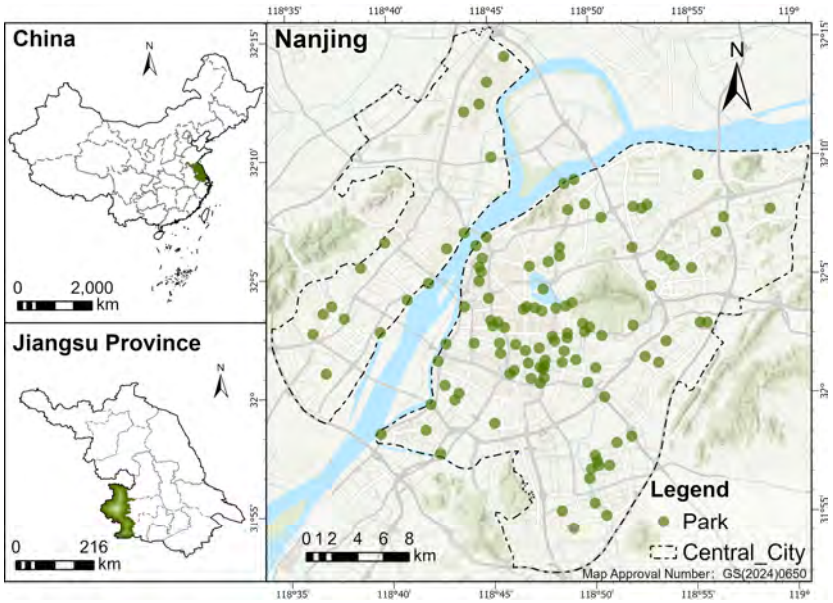

Fig. 1: Location of the study area

2.1 Data Sources and Pre-Processing

High-resolution satellite imagery with a spatial resolution of 0.5m was used. The internal land cover types of the parks were precisely delineated using object-oriented analysis and a Random Forest classifier, and categorized as forest, grassland, water, and impervious surface. The overall accuracy of the classification results was 89%. Based on the classification results, landscape pattern indices within the urban parks were calculated using Fragstats 4.3. Vegetation cover was represented using the normalized difference vegetation index (NDVI) with a spatial resolution of 30 m, as provided by YANG et al. (2019). Canopy height within parks was calculated based on a global high-resolution canopy height dataset with a spatial resolution of 10 m (LANG et al. 2023). Building height data were derived from vector datasets obtained from Bigemap.

The average level of crowding within parks was calculated using population heatmap data from the Baidu Map Huiyan platform. According to the Urban Green Space Planning Standard (GB/T 51346–2019), buffer zones with service radii of 300 m, 500 m, 1,000 m, 2,000 m, and 3,000 m were established for parks with areas of 0.4–1 ha, 1–5 ha, 5–10 ha, 10–20 ha, and greater than 20 ha, respectively (LI et al. 2020). Densities of scenic spots, catering services, and public facilities (e. g., public toilets, emergency shelters, newsstands, and public telephones) within park buffers were calculated to characterize surrounding infrastructure conditions. Park accessibility was assessed by calculating the density of bus stops within park buffers using the Chinese public transport network vector dataset (WANG et al. 2025). Air

quality within park buffers was represented by the aggregated concentration of air pollutants derived from the high-resolution and high-quality air pollutants dataset for China (CHAP), including seven conventional near-surface pollutants (PM_1, PM_{10}, $PM_{2.5}$, SO_2, O_3, NO_2, and CO), with a spatial resolution of 1 km.

Table 1: Park Landscape Metrics

Category	Indicator	Abbreviation	Description
Landscape Level	Total Area	TA	Area of the park
	Total Edge	TE	Length of the park boundary
	Landscape Shape Index	LSI	Measure of landscape shape complexity
	Aggregation Index	AI	Connectivity among patches
	Landscape Division Index	DIVISION	Overall degree of landscape fragmentation within the park
	Shannon's Diversity Index	SHDI	Indicator of landscape heterogeneity
Class Level	Class Area	CA	Area of patches for each land cover type
	Edge Density	ED	Boundary length per unit area for different land cover patches
	Aggregation Index	AI	Connectivity among patches of different land cover types
Vegetation Coverage	Normalized Difference Vegetation Index	NDVI	Mean NDVI of the park
Vertical Structure	Canopy Height	CH	Canopy height within the park
	Building Height	BH	Height of buildings within the park
Crowding Level	Crowding Level	CL	Average level of crowding within the park
Park Infrastructure	Points of Interest	POI	Density of scenic spots, catering services, and public facilities within the buffer zone
Accessibility	Density of Public Transit Stops	PTRD	Density of bus stops within the buffer zone
Air Quality	Concentration of Air Pollutants	AP	Aggregated concentrations of seven air pollutants (PM_1, PM_{10}, $PM_{2.5}$, SO_2, O_3, NO_2, and CO) within the buffer zone

2.2 Fine-Grained Aspect-Level Preference Analysis Based on LLMs

To comprehensively investigate public preferences for urban parks, this study collected user-generated reviews from Ctrip and Dianping for 117 urban parks up to May 2025, yielding a total of 107,714 comments. The extracted fields included review ID, username, review text, timestamp, and location. After necessary data cleaning and preprocessing, 107,542 valid reviews were retained for analysis. A large language model, Qwen3, was employed to conduct fine-grained, aspect-level sentiment analysis of the social media texts, with public preference scores quantified through few-shot learning and prompt engineering. During inference, de-

terministic decoding was adopted with a fixed maximum generation length, producing structured outputs that were subsequently parsed into discrete labels.

The core of few-shot learning lies in enabling a model to rapidly understand task requirements and generalize to new data using only a small number of manually annotated examples (BROWN et al. 2020). In this study, five samples were manually annotated for the four dimensions of complexity, coherence, legibility, and mystery, covering the sentiment categories of positive (1), negative (-1), and not mentioned (0). Annotation was independently performed by two experts in the field of landscape architecture and reviewed by a third expert to ensure the professionalism and consistency of the annotation results. A limited number of annotated examples were embedded in the prompt, combined with explicit task instructions (defining the model as a domain expert tasked with judging the sentiment polarity of the four aspects), aspect definitions (clearly specifying the four preference dimensions), and judgment rules (positive cues, negative cues, neutral rules, conflicts, and edge cases), guiding the model in learning how to determine whether a specific aspect was mentioned in the review and its sentiment tendency. This process enabled automated and consistent sentiment classification for the large-scale unannotated data. A random sample of 300 reviews was manually annotated to serve as the model's validation set. Model performance was evaluated using precision, recall, and F1-score as evaluation metrics (Fig. 2).

2.3 Statistical Analyses

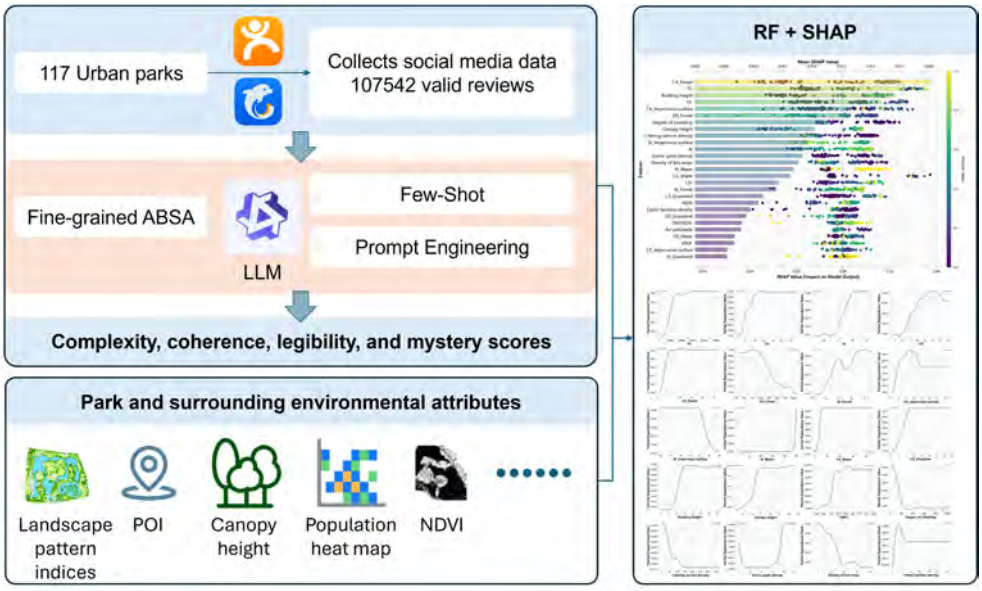

Fig. 2: Research framework

The average value of complexity, coherence, legibility, and mystery, derived from LLM sentiment analysis results, was calculated and used as the public preference score. A Random Forest model was employed to evaluate the relative importance of park and environmental features on public preference. The dataset was split into training and testing sets at an 8:2

ratio. Bayesian optimization was applied for model parameter tuning over 50 iterations, and 5-fold cross-validation was performed to ensure the model's reliability. The contributions of predictive variables to the model's predictive capability was analyzed using SHapley Additive exPlanations (SHAP), and Partial Dependence Plots (PDPs) were used to reveal the nonlinear influences of variables on park preference.

3 Results

The results demonstrate that the micro-average precision, recall, and F1 score were all 0.879, indicating that the model maintained stable and high accuracy at the overall sample level. In contrast, the macro-average precision, recall, and F1 score were 0.718, 0.830, and 0.751, respectively. This suggests that the model's performance varied somewhat across different classes but remained generally stable and balanced overall. Furthermore, the model's classification performance varied across different preference aspects. The mystery aspect achieved a precision, recall, and F1 score of 0.771, 0.853, and 0.798, respectively, demonstrating the model's relatively accurate identification of this dimension. The higher recall (0.849) for complexity (F1 score = 0.773) indicates a strong ability of the model to identify complexity. The F1 scores for coherence and legibility were 0.731 and 0.716, respectively, which, although slightly lower than the other attributes, still represented an acceptable level.

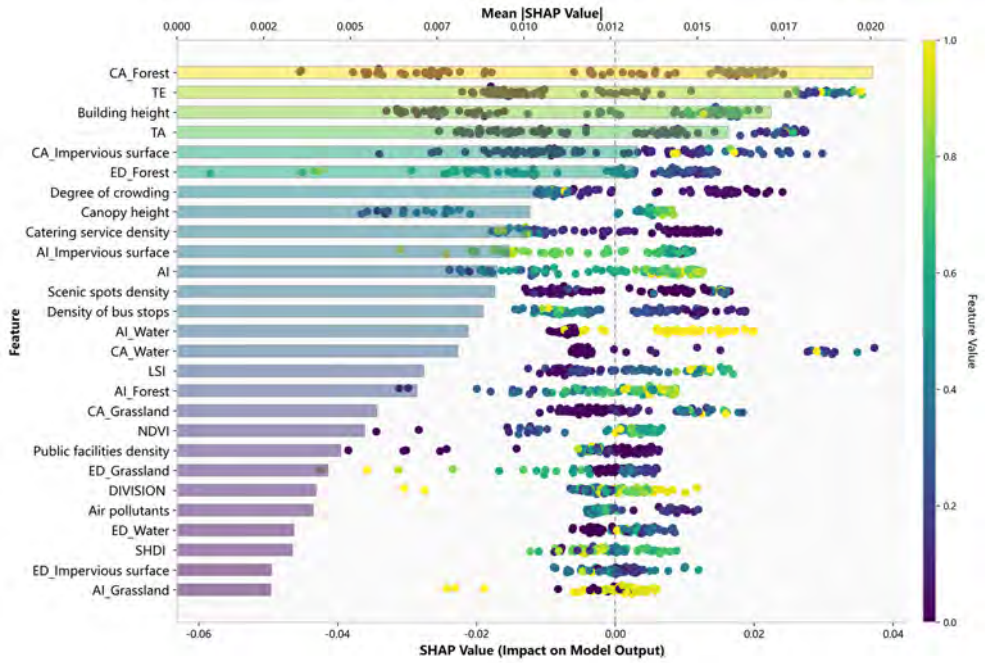

Fig. 3: SHAP Summary Plot

In terms of importance ranking, the top six variables were CA_Forest (forest area), TE (total park edge length), TA (park area), ED_Forest (forest edge density), building height, and canopy height (Fig. 3). Partial dependence plots (PDPs) further revealed the nonlinear relationships between park and environmental characteristics and public preferences (Fig. 4). Public preference increased with park area, exhibiting a threshold effect at 22 ha. Similarly, preference rose with total park length and plateaued beyond 30,000 m. AI was positively associated with preference. Preference increased with LSI, but began to decline when LSI exceeded 30. Forest edge density exhibited a threshold effect at 800 m/ha.

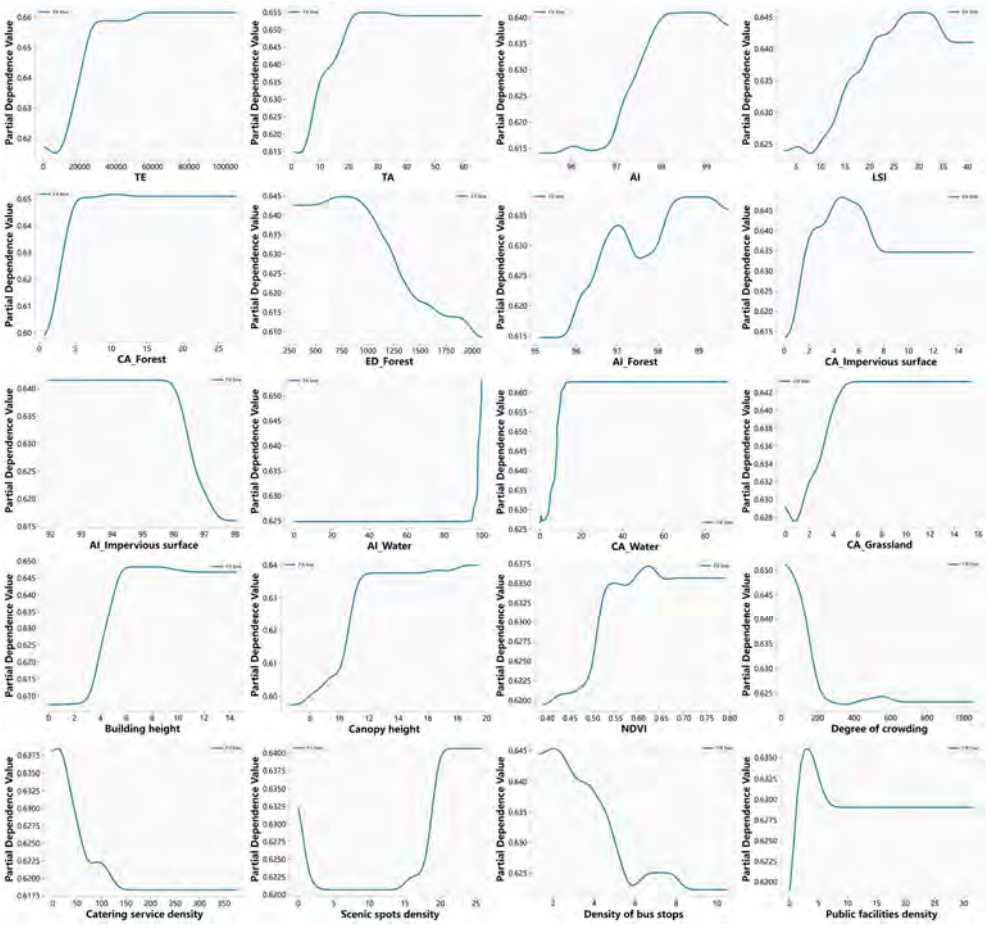

Fig. 4: Dependence Plot

The effects of the areas of forest, grassland, and water within parks exhibited threshold effects, with preference rising sharply initially and plateauing once certain levels were reached. In contrast, impervious surface area demonstrated an inverted U-shaped relationship with preference. The aggregation of forest and water was generally positively associated with preference, whereas aggregation of impervious surface was negatively associated. Building

height had a positive effect, with a threshold at 9 m. Canopy height also showed a positive relationship. NDVI values of 0.60–0.65 corresponded to the highest levels of preference, highlighting the positive role of vegetation cover.

Park crowding exhibited a clear negative correlation with preference. The density of scenic spots positively influenced preference. Preference was highest when catering service density was below 50 establishments per km², indicating that excessive commercial density may introduce negative factors such as noise and environmental commercialization. Bus stops density was optimal at 2-3 stops/km², and preference peaked when public facilities density was 2-5 per km².

4 Discussion

Compared with traditional approaches, LLMs exhibit notable advantages. Conventional sentiment analysis methods include rule-based and lexicon-based approaches, as well as supervised machine learning models. The former rely on predefined vocabularies and polarity rules, making them inadequate for handling semantic ambiguity and complex contextual expressions; the latter incorporate statistical features but remain heavily dependent on annotated data and feature engineering, limiting their adaptability to domain transfer and highly heterogeneous texts. Although deep learning and pre-trained language models have improved representation capabilities, they still require supervised fine-tuning, and their scalability is constrained by data and computational resources (LEON 2025). In contrast, LLMs, pre-trained on large-scale unsupervised or weakly supervised data, possess stronger general language understanding and reasoning capabilities, enabling them to perform complex sentiment and aspect recognition tasks under few-shot or even zero-shot conditions (LUO et al. 2025). The findings of this study indicate that the model performs well at the global level and demonstrates good generalization across categories.

However, relatively lower F1 scores were observed in dimensions such as coherence and legibility. This may be attributable to the fact that these dimensions often involve metaphorical expressions, emotional connotations, and cultural imagery. LUO et al. (2025) noted that certain latent cultural ecosystem service types remain challenging to identify. In contrast, topics that are more concrete or closely tied to physical space tended to achieve higher accuracy and F1 scores (WEI & HOU 2023). These observations suggest that, although LLMs excel in language generation and contextual comprehension, there remains room for improvement in precise reasoning of highly abstract concepts, accurate metaphor interpretation, and cross-text semantic consistency (LUO & SPECIA 2024). Future research may incorporate human review during the model output stage, establishing a hybrid human-model decision-making system, to maintain high reliability and interpretability through continuous calibration (RETZLAFF et al. 2024).

The results highlighted the critical roles of park area and boundary configuration, with a threshold value of 30 identified for the Landscape Shape Index (LSI). This finding indicates that landscape patches with a moderate degree of complexity and irregularity are more strongly preferred, likely due to their longer edge lengths and richer visual variation. Well-designed and deliberately organized boundaries enhance visual layering and spatial legibility, thereby increasing the attractiveness, recreational vitality, and utilization of parks (LI et al. 2020). The analysis further showed that large, coherent blue–green spaces are more favored

than fragmented patches. In high-density urban centers, where residents have limited opportunities to access pristine natural environments, the aggregation of large-scale natural patches not only reinforces continuous green visual corridors but also facilitates more immersive nature experiences. This preference can be interpreted through the Biophilia Hypothesis, which posits that humans have an innate affinity for environments with natural attributes and high ecological integrity (WILSON 1984) The positive effect of building height suggests that relatively lower buildings are conducive to accommodating public service facilities and contribute to the formation of a strong sense of place and aesthetic quality (ZHAO et al. 2025). In addition, canopy height exhibited a positive influence on public preference. Taller trees and more mature forest structures provide shaded and secure landscape settings, fostering a more comfortable natural atmosphere (LEHTO et al. 2024).

Moreover, crowding level emerged as a key factor triggering negative visitor emotions. The proximity of park clusters and the availability of diverse landscape resources are associated with improved public preferences. Adjacent green space networks not only enhance ecological connectivity but also generate more attractive landscape experiences at the psychological level (CHEN et al. 2020, LEE et al. 2024). Finally, improvements in basic infrastructure enhance accessibility and experiential comfort. This finding is consistent with Rational Choice Theory, which suggests that infrastructure reduces travel costs and enables individuals to more readily obtain the benefits of landscape experiences (KEBEDE 2020).

This study has several limitations. Large scale online reviews from social media platforms (e. g., Dianping, Ctrip) may not fully or objectively represent the experiences of all park users, particularly underrepresenting the opinions of older adults and children. Additionally, this study primarily examines the overall associations between park and environmental features and public preferences, without fully modeling complex spatial effects such as spatial autocorrelation. Future research should incorporate spatial econometric methods to provide complementary tests of potential spatially correlated features.

5 Conclusion

In summary, the model effectively captured and evaluated preference information regarding the four aspects of complexity, coherence, legibility, and mystery from public comments, confirming the substantial application potential of the LLM-based fine-grained ABSA method in advancing landscape perception and preference research. This approach offers a novel perspective for understanding public fine-grained preferences for urban parks on a large scale. Furthermore, the results indicate that park area and total edge exhibit positive threshold effects, with thresholds of 22 ha and 30,000 m, respectively. The results highlight the critical role of sufficient and coherent blue-green spaces, high-quality vegetation cover, appropriate morphological complexity (with an LSI threshold of 30) and facility configuration, and the control of crowding and excessive hardscaping in enhancing public preference and experience of parks. These findings provide data-driven scientific recommendations for optimizing urban park design, improving park service quality, and maximizing the social and ecological benefits of parks.

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Toward a Framework for AI Ethics in LA

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Abstract: This paper presents a review of artificial intelligence (AI) ethics literature to identify paths that could be fruitful in developing ethical guidelines for AI applications in landscape architecture (LA). One complication comes from the different ways that AI manifests in design, resulting in a suggested framework with three dimensions of AI in LA: underlying structural types of AI; areas of application for AI; and categories of ethical concerns. The framework can support specificity and conceptual exploration as the community identifies both principles and guidelines for AI ethics in LA.

Keywords: Artificial intelligence, ethics, landscape architecture

1 Introduction

What ethical guardrails could help landscape architecture (LA) identify uses of artificial intelligence (AI) as inappropriate or dangerous? A notable paper at DLA 2025 reported an update on the current use of artificial intelligence (AI) in landscape architecture (LA) (BRAIDEN et al. 2025). A clear message of the paper was that AI is now being integrated into everyday landscape architectural practice. But the survey also found that practitioners were concerned about ethical considerations, including intellectual property rights infringement and business ethics. Not only are practitioners using the largely untested technology in professional practice, but it is also increasingly present in the classroom as a pedagogic tool, in student work (acknowledged or not), and as the focus of the lesson (CANTRELL et al. 2021, LIU 2024).

While there is an increasing amount of literature on applications and innovations of artificial intelligence in LA (FERNBERG & CHAMBERLAIN 2023), it is alternately seen as promising, inevitable, threatening, and/or mysterious. It can be difficult to square headlines reporting that "The A.I. Time Bomb Is Ticking" (WITT 2025) with "Urban planners should not be afraid of AI" (MALEKZADEH 2026). And, while the literature often recognizes or warns of ethical considerations, it often offers less guidance on how the landscape architectural community should respond. It is essential that the profession develop its own distinct approach because its position is equally distinct: "While all of the design professions are being forced to confront their conceptions about the roles of computers in design, the spatial complexity and defensible decision processes needed for many geodesign projects makes this critical reconsideration of the computer all the more important for this emerging field" (TULLOCH 2016).

Despite the many peculiar and unique qualities of landscape architecture, examples of frameworks and guidance from allied fields can help give us a general direction. For example, a proposal for Sustainable Cities endeavored to tie different AI ethical principles to the elements of the UNESCO Sustainable Development Goal, SDG-11. Many of SDG-11's goals and underlying values are shared with landscape architecture, but the ways in which AI will be used and understood are distinct. This raises a question of whether landscape architecture has such an identifiable central structure for its goals and expectations. A recent paper in the area of cultural heritage, a more narrowly defined field, proposed a framework that included

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a list of six prerequisites for an AI system to be considered trustworthy and a paired set of ethical pitfalls and ethical principles (PANSONI et al. 2023).

As a starting point, this paper uses literature from both landscape architecture and other fields to frame the arena within which AI use may parallel or inform a framework for LA. As such, different dimensions of ethical concerns seem likely to emerge through:

- underlying structural types of AI;
- areas of application for AI; and
- categories of ethical concerns.

As part of this initial exploration, the paper uses previously published examples of AI applications in LA to illustrate different loci within the framework and different lessons that might result. It concludes with suggestions that risk reaching beyond the findings, but are meant as illustrations of possible steps forward.

2 Frameworks for Ethics in Landscape Architecture

The American Society of Landscape Architects (ASLA) first published a Code of Professional Ethics in 1927 (VERNON 1987). There had been resistance; codes of ethics and similar standards often are first seen as ineffective. In 1916, Frederick Law Olmsted, Jr. voiced his objection to the development of a Code of Ethics for Landscape Architecture:

> No formal ethical code is really necessary for a clear-thinking honorable man: no such mechanical list of rules can safely be substituted for clear-thinking; and no such code will suffice to control the few men whose motives are dishonorable. That is why I am glad our Society does not attempt to set up any formal detailed code of ethics. (OLMSTED 1916)

By 1927, the ASLA saw a greater need for a code. In that moment, it served as a declaration that landscape architecture had arrived as a fully mature profession. In addition, the code was understood less as a tool for preventing unscrupulous practice and more as a means of addressing those bad actors. “Professionals actually develop ethical codes to protect themselves from unethical colleagues,” which the ASLA recognized with a mechanism for the fellows removing those unethical colleagues (VERNON 1987).

Nearly 100 years later, the ASLA regularly updates and tweaks the code, albeit with slightly different purposes, but consistent with the basic notion of upholding a professional standard for the Society’s members. Today the ASLA maintains both a Code of Professional Ethics and a Code of Conduct. The continued evolution of the ASLA resulted in an additional code addressing a substantial area of concern, the Code of Environmental Ethics, which was first adopted by the ASLA board in 2000. This document established the ASLA’s commitment “to responsible ecological stewardship in planning, design, management, and policy,” while providing some guardrails to suggest professional standards within the code. The code is framed with a set of Foundational Values and then lists specific Ethical Standards for acting on the code (ASLA 2026).

As a parallel, the International Federation of Landscape Architects (IFLA) has developed and approved Global Ethical Principles for Landscape Architecture. This document provides seven overriding principles guiding ethical practice with specific considerations for each

principle, “ensuring public confidence and trust in the landscape profession.” (IFLA 2026) Some of the principles establish foundational ethical expectations about the impacts of practice on our communities and the planet. The first principle establishes this notion of the greater role of our profession: “Principle 1: Landscape architects promote conservation and enhancement of the environment and quality of life for now and future generations.” Others are more pragmatic in the way they establish expectations and address the different contexts in which IFLA membership might function. For example, “Principle 4: Landscape architects comply with national and international law.”

Learning from these precedents, it seems likely that a code of ethics for AI in LA would include both principles and standards that together help establish lofty yet practical expectations.

3 The Arena – 3 Dimensions of AI Ethics In LA

3.1 Underlying Structural Types of AI

A fundamental challenge in framing ethical concerns are the underlying structural types of AI technology that might proliferate in landscape architecture. Each structural type of technology might be associated with different ethical questions or conflicts. For example, Generative AI and Large Language Models (LLMs) require significant amounts of intellectual property (IP) for use in their training models. In contrast, the increasingly popular plant identification applications use deep learning and Convolutional Neural Networks (CNNs). The use of these underlying engines raises different implications about IP, autonomy, energy use, and a variety of other ethical concerns.

For landscape architecture, a possible list of AI structural types could include:

- Large Language Models (LLM)
- Generative AI
- Reactive AI
- Machine learning
- Deep Learning and CNNs
- Robotics

Given the diverse structural types, an ethical framework should recognize these differences as one dimension of landscape architectural AI. As will be true with the other dimensions below, this list could be grouped to shorten it, or lengthened by acknowledging its fineness. Certainly, as the framework evolves and discussions of AI ethics advance, new structural types will continue to emerge.

3.2 Areas of Application For AI

The areas of application for AI in LA also bring substantially different ethical implications, independent of the questions associated with the structural type. Using an LLM to specify plant materials is a different ethical arena than using that same LLM for converting the construction document for a concrete pad in an urban park into the construction document for a concrete pad in a rural nature preserve parking lot. Most importantly, each brings different combinations of AI ethics concerns.

The recent surveys of AI usage (FERNBERG & CHAMBERLAIN 2023, BRAIDEN et al. 2025) and examples of applications suggest that areas of application could be categorized as:

- Imagery/Illustration
- Community involvement
- Design
- Construction
- GeoAI and RS interpretation
- Writing code for apps
- Policy analysis
- AI as a teaching tool
- Teaching AI

These application categories will continue to combine AI types and products as they transition from creating answers, documents, spatial forms, and graphics.

3.3 Categories of Ethical Concerns

While new fears seem to pop up almost daily (most recently, YUDKOWSKY & SOARES 2025), the LA community can attempt to categorize them in ways that help anticipate new ethical quandaries and may guide the eventual development of ethical principles or policy actions. For example, LIU (2024) specifies ethical concerns of: Intellectual Property and Authorship; Accuracy and Misinformation; and Labor and Automation. These groupings are based loosely on ethical concerns raised in other fields (NGUYEN et al. 2023, PASTOR-ESCUREDO, TRELEAVEN & VINUESA 2022, SANCHEZ, BRENMAN & YE 2025) but fitted to issues more linked to applications in LA:

- AI-Energy/Water consumption
- Workforce/jobs
- Bias
- Accuracy and Misinformation
- Intellectual Property
- Equity and Mis/Under/Representation
- Privacy
- Transparency
- Accountability
- Recognizing scale
- Physical safety

The ethical concerns still serve broadly as categories that are not mutually exclusive. While crisply defined boundaries might not be needed, concerns can serve as linkages to potential principles that could guide future decisions.
Taken together, these three dimensions attempt to capture potential combinations for the majority of examples in landscape architecture. As a first step, they serve as an immediate reminder that AI use and AI challenges represent a complex multidimensional arena that will not be neatly addressed with a simple set of expectations or understandings.

4 Informed by Examples of AI in LA

Moving ahead, a growing number of examples of AI in LA can inform the development of the structure of the framework as well as the discussion of resulting principles and ethical standards. As new examples emerge (e. g., ASHARI, AMOROSO & KELLY 2022, ASHARI & SHAFAGHATI 2025, REKITTKE & HAYLES 2025), their approximate locations within the three dimensions of AI ethics in LA can highlight patterns as well as gaps. Hypothetical or proposed uses may also be useful in casting a wide net that raises concerns before they become practical issues.

A challenge is that published examples, especially within professional and scientific literature, will be carefully developed with some ethical hurdles having been carefully averted. Successes get published more than failures and problems. Our community may need to capture nascent efforts or examples beyond the traditional boundaries of the field. For example, a recent USA Today column encouraged broader use of AI instead of hiring professionals and displayed a design completed using ChatGPT (JOLLY 2025). This example used a complex AI tool (both Generative and LLM) for design, plant selection, and construction documents. The ethical questions attached to this application would include AI-energy/eater consumption, workforce/jobs, intellectual property, physical safety, and accountability. But it also raises a different question about the quality of the final project.

5 Developing Principles and Standards

A shared framework, even if it is still evolving, could serve as a foundation for developing broad principles and specific guidelines that communicate the commonly understood interests of the landscape architecture community. These principles and standards are the potential targets and guardrails.

As a potential model for this, UNESCO (2022) developed a Recommendation on the ethics of artificial intelligence. Included in this are a series of general principles that establish an ethical perspective for key topics, such as the principle on Transparency & Explainability: “The ethical deployment of AI systems depends on their transparency & explainability (T&E). The level of T&E should be appropriate to the context, as there may be tensions between T&E and other principles such as privacy, safety and security.” These principles aren’t hard and fast rules, but they do open the door and point clearly in a direction that has been previously agreed upon. An ethics review of the UNESCO Recommendations (2022) undertaken by GANBAATAR (2025) suggests a different perspective on the utility of such guidance, saying that it should be seen as “an invitation to take a principled stance towards a more just, inclusive and ethically grounded digital future.”

Most importantly, the development of a framework or code needs to reflect perspectives and expectations that are shared across much of the professional community. The UNESCO approach recognizes that aspirational approaches need to integrate attainable and realistic expectations if its guidance is to be widely used. The popularity of AI will not be undermined by onerous expectations that are not embraced by those implementing AI applications.

6 Which Way Forward?

Landscape architecture needs clear and broadly accepted ethical guidance for AI in LA.

It is not the intention of this paper to set an ethical standard for AI in LA, but it serves as an invitation for the LA community to take AI discussions, the arena, and the guardrails more seriously. In a recent Editorial in *Landscape Research*, Hannes PALANG (2025) recognized that artificial intelligence had become an unavoidable topic in landscape architecture and raised the concern that "what seems to be missing is how AI relates to landscape justice." As such, this invitation has a sense of urgency.

The most important step forward is the start of a conversation toward developing ethical guidance for AI in LA. That conversation could happen within a formalized structure – like IFLA, ASLA, CELA, or DLA – or through a more ad hoc group. Such a group would need to address the myriad forms and uses of AI in LA in order to craft useful guidance. And that group could collaborate with other professions, but needs its core to be focused on LA issues and guidance.

Some readers may doubt whether landscape architecture, as a smaller profession, would be better served to piggyback on the work of other professions and professional groups. Certainly, we should learn whatever we can from the work of other fields and disciplines, but landscape architecture has distinct conditions and needs that will not be fully addressed by other groups. For example, the environmental or planning communities may have invaluable insights on tools that generate information to support complex decisions, but could leave unanswered many concerns about creativity and form-generating uses of AI. Similarly, our allied design colleagues in architecture may inform thinking about form, construction, or safety, but may have very different value systems when considering external impacts. Any meaningful framework for AI and LA will be unique.

As suggested earlier in sections 3 and 4, an immediate step could be to develop a more structured library of examples documenting how AI is actually being used in LA. These examples could be supplemented with hypothetical scenarios to address the rapidly evolving nature of AI and the high costs associated with some applications.

Finally, as potential principles are developed, they need to be tested against emerging practice and professional realities. For the sake of conversation, this paper offers five initial principles that can be used to spark further questions and discussion:

When using artificial intelligence, landscape architects should…

1. Acknowledge and credit the use of AI in landscape architectural projects and research
2. Retain responsibility and accountability for the health, safety, and welfare of the users of their designs
3. Be aware of the sourcing of AI training materials and any related implications.
4. Recognize the potential for applications to favor (or disfavor) one group over others
5. Use representations and visualizations that do not misrepresent intentions or specifics

Readers should be mindful of these initial offerings as simply the starting point for a conversation about ethical guidance for landscape architecture.

Expectations need to be tempered; a realistic approach will not guarantee clarity. Ethical guidelines will provide tremendous help but they will not prevent quandaries and conundrums, and certainly will not prevent deliberate misuse. But, a key premise in ethics posits that discussion can lead to increased shared understandings and a platform when organizations like IFLA, LAF and ASLA can broaden discussions and collaborations. Meaningful ethical standards are best developed through community conversations and achieved through consensus, but the rapid pace of new AI development may require different approaches if any meaningful guidance is to be broadly adopted. Whatever the approach, our communities need to move forward because we have reached a time when landscape architecture needs clear, broadly accepted ethical guidance for AI in LA.

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Empty Lots, Hidden Potential: A Feasibility Study for AI-Driven Rethinking of Urban Parking Demand

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Abstract: Urban parking lots occupy a significant portion of land in the United States, with nearly 15% of urban areas dedicated to vehicular parking. Despite extensive documentation of parking allocation, a comprehensive analysis of usage patterns is lacking. This study leverages remote sensing imagery and computer vision to monitor parking lot occupancy across Salt Lake City, USA, revealing a marked decline in usage between 2018 and 2021. The findings highlight the potential for more efficient land use, suggesting that accurate data can inform municipal code revisions and support development initiatives to repurpose underutilized spaces for community and environmental benefit.

Keywords: Computer Vision, transportation, parking, sprawl, land use

1 Introduction

Globally, parking lots occupy vast areas of land. Specifically, in the United States, substantial portions of urban land are allocated to parking lots. Recent estimates suggest that approximately 0.3% of the land in the continental U.S. is dedicated to parking lots (GARBER et al. 2024), while about 2% of the lower continental U.S. is classified as an urban area, including suburban spaces. This implies that nearly 15% of all urban land serves vehicular parking needs. The allocation and evolution of parking spaces have been thoroughly documented (SHOUP 2021), and evidence indicates that demand for parking may decline in the future (MERTEN & KUHNIMHOF 2023). Demand for parking may continue to decrease as the rise of home delivery services increases, shifting consumer habits as brick-and-mortar businesses adapt, and the growing prevalence of remote and hybrid work arrangements, which reduce daily commuting. While U.S. cities have extensive underutilized land, including low-use parking lots (Manville & Shoup 2005), objective, systematic, and scalable methods to evaluate these sites for potential redevelopment are limited.

Most local inventories of parking usage rely on outdated surveys or manual inspection, while there are new means to explore the relationship between parking and the function it serves more broadly (TANG et al. 2025). Despite several city-level studies examining parking lot usage, there remains a lack of comprehensive analysis regarding overall demand, patterns, and utilization of these spaces. Given the significant amount of land devoted to parking, it is prudent to enhance our understanding of actual usage. Such insights may inform innovative strategies for infill development and the advancement of urban planning initiatives. Various camera-based technologies are available for assessing parking lot usage; however, these solutions are typically designed for individual locations and do not provide comprehensive data on regional utilization.

This presents an opportunity for AI-assisted remote sensing to assess land-use efficiency because it could provide a scalable method. This paper examines the use of remote sensing imagery, in combination with machine learning methods, as an effective means to monitor

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parking lot occupancy accurately and efficiently throughout the year. Such data can inform revisions to municipal codes to better reflect actual usage patterns and may also support development initiatives aimed at repurposing underutilized land for greater benefit to the community and environment. The specific research question is: to what extent is it technically feasible to use AI-based object detection on remote sensing imagery to identify parking lot usage? Specifically, this paper presents a proof-of-concept study rather than a comprehensive trend analysis. The study is limited to four parking lots and two time points to demonstrate technical feasibility. A discussion of opportunities, limitations, and an outline of future research directions for scaling this approach is presented.

2 Feasibility Study Approach

This study employed high-resolution aerial imagery from the National Agriculture Imagery Program (NAIP) to evaluate the potential of computer vision for detecting parking lot occupancy. While NAIP provides valuable coverage, its limitations – such as infrequent acquisition intervals and sensitivity to seasonal and lighting conditions – restrict its use for continuous monitoring. In this proof-of-concept, NAIP imagery serves primarily to demonstrate the broader applicability of remote sensing for automated detection rather than as a definitive operational dataset. Previous research has explored similar applications of NAIP for object detection, underscoring its utility despite these constraints (BAZRAFKAN et al. 2025, HUANG & JIN 2022). For higher precision and temporal granularity, alternative data sources such as UAV-based imagery, fixed parking lot cameras, or commercial satellite platforms (e. g., PlanetScope) offer promising options. However, many parking facilities lack such localized data, making scalable approaches using publicly available imagery an important consideration.

To assess the satellite imagery, this project employs YOLO (You Only Look Once, REDMON & FARHADI 2018) and Faster R-CNN (BENJDIRA et al. 2019, AMMAR et al. 2019). These were selected because they are well established in remote sensing and urban object-detection applications, where both accuracy and efficiency are important. YOLO version 5 was used because it enables simultaneous localization and classification, making it suitable for large-scale imagery. YOLO is often used for real-time applications (which was not necessary for this experiment), and it also offers a scalable solution for large-area applications. YOLO can be used for image classification or semantic segmentation; for this study, object classification was chosen because it enables counting individual vehicles within a given area.

To construct the required training dataset from NAIP imagery, a representative aerial scene was first selected and subdivided into smaller sections (Fig. 1). The source image was tiled into 128 × 128 pixel patches to facilitate efficient manual inspection and labeling while preserving sufficient spatial context for identifying vehicles and parking spaces. From this pool of tiles, 50 samples were randomly selected after removing images that did not contain any vehicles or parking spaces, ensuring that all training examples contained relevant objects of interest and avoiding dominance by background-only samples. The selected tiles represent a wide range of parking configurations, textures, lighting conditions, and vehicle densities.

Objects intended for automatic identification need to be trained by annotating (labelling). RoboFlow was used to produce these annotations because it works seamlessly with YOLOv5 and its built-in support for dataset versioning and augmentation. Two object classes, “Car”

and “Parking Space”, were defined, and all selected images were labeled using bounding boxes (Fig. 2). The dataset was split into 80% for training and 20% for validation. To enhance robustness given the limited sample size, a series of data augmentations was applied during export, including horizontal and vertical flips, random cropping (0-30% zoom), rotations (±8°), brightness adjustments (±25%), and slight Gaussian blur (up to 0.8 px). These operations expanded the dataset to 130 images and introduced controlled variability in scale, orientation, and illumination, helping to reduce overfitting and improve generalization. All images were exported at a resolution of 640 × 640 pixels, which is the default input size for YOLOv5 and provides an effective balance between detection accuracy and computational efficiency for small-object detection in aerial imagery.

Fig. 1: Depicts 50 of the 130 images used to train the YOLO model to detect parking spaces and vehicles. The set of images represents a wide range of conditions within the study region.

To assess the feasibility of this approach, four study sites (Fig. 3) were selected within the greater Salt Lake City Metro Area, an urban environment characterized by extensive roadway infrastructure and numerous parking facilities. The study sites were delineated via Google Earth Pro. High-resolution aerial imagery was obtained from the U.S. Geological Survey using the National Agriculture Imagery Program (NAIP) for the years 2018 and 2021, with a resolution of about 1 meter. These data were collected around the same time of year. These time periods coincided with the COVID-19 pandemic. This alignment was intentional, as the timing of the imagery corresponded with a significant shift in commuter parking lot usage, thereby facilitating the identification of distinct utilization patterns and improving the likelihood of selecting representative sample sites. These images were then clipped and converted into high-quality PNG formats to facilitate machine learning and deep learning model development focused on parking lot utilization analysis.

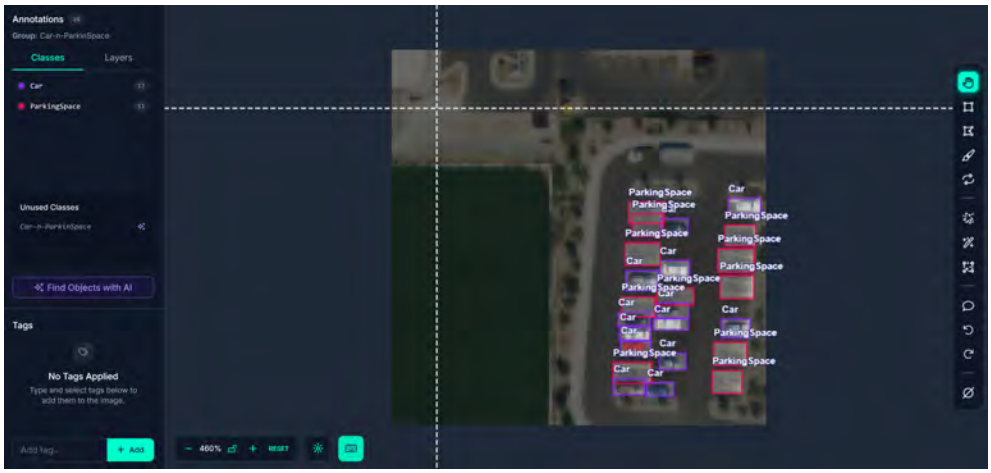

Fig. 2: Example of image labelling process using Roboflow. Labeling is a manual process whereby vehicles and empty parking spaces are drawn by using bounding boxes (purple and red, respectively).

Fig. 3: The study utilized four parking lots of varying sizes and capacities. Yellow shapes delineate the designated parking spaces for each lot. The lot in the top left is the largest, offering approximately 500 parking spaces, while the bottom left lot is smaller, accommodating around 200 vehicles.

3 Findings

The training and validation loss curves showed steady improvement and convergence, indicating effective learning without overfitting. The model achieved a mean Average Precision (mAP@0.5) of 0.46 overall (Fig. 4), with higher accuracy for cars (mAP 0.636) than for parking spaces (mAP 0.284). The model correctly detected 80% of cars, indicating strong performance for this class. Similarly, parking spaces were correctly detected 80% of the time based on the Confusion Matrix. However, there is some overlap and misclassification between cars and parking spaces, suggesting that the model sometimes confuses the two. A summary of actual parking lot usage was developed to compare the two years.

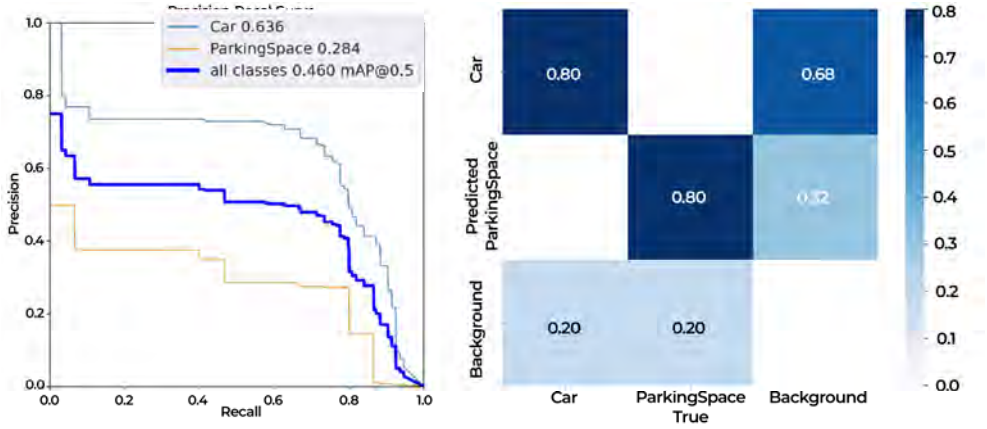

Fig. 4: Precision-Recall Curve and mAP (left) and Confusion Matrix (right)

Between 2018 and 2021, occupancy rates across four parking lots decreased markedly. In 2018, the majority of lots exhibited high utilization, with rates spanning from 64% to 87%. By 2021, these figures had declined substantially, ranging from 13% to 46%. Notably, only one lot maintained close to half its prior usage, whereas the others experienced significant declines. This trend aligns with expectations, as the COVID-19 pandemic in 2021 greatly reduced vehicular travel (DU et al. 2021). Our results were corroborated by manual calculations, with a margin of error between the computer vision model and manual vehicle counts remaining under 3% across all parking lots.

4 Discussion

The findings from this proof-of-concept study have the potential to inform dynamic evaluations of parking patterns and occupancy rates over time. This could offer critical insights for both contemporary urban planning and future transportation infrastructure initiatives. As a demonstration of feasibility, this process indicates that accurate analyses of parking lot usage are likely achievable.

However, detecting and characterizing parking lots and vehicles from remotely sensed imagery remains challenging. Even with NAIP's 1-meter resolution, cars can be difficult to

distinguish due to lighting variation, shadows, and low-contrast surfaces. Higher spatial and temporal resolution would improve detection and allow more accurate distributions of parking-lot usage over time. Model training also requires larger, more representative datasets that capture differences in vehicle form and color (sedans, trucks, SUVs) and surface variability (asphalt versus concrete, faded striping, angled layouts, planter strips). Rendering artifacts, inconsistent pavement markings (EV charging, designated disability), and shadows often reduce reliability, as may permanent structures of similar size to vehicles. Seasonality introduces further limitations – tree canopies in summer can obscure vehicles, while winter imagery increases visibility but changes reflectance and surface texture (e. g., snow).

Future research should combine multi-temporal imagery with improved object-detection models, contextual labeling, and seasonal correction methods to enhance accuracy. The current dataset of 130 images is insufficient for robust training, so expanding the dataset size would significantly enhance performance. Improvements in parking space detection might be achieved by increasing the number of samples or refining the annotations for a broader range of elements and configurations.

Achieving accurate estimates of parking lot usage will require higher temporal resolution than NAIP provides. There are several commercial satellite platforms available that can provide near-daily coverage at slightly lower resolution than NAIP (though perhaps not detailed enough for detecting individual vehicles), companies that provide similar resolution throughout various times of the year, and taskable high-resolution systems that could be used to support targeted monitoring during peak periods. Complementary approaches, such as deploying UAVs for on-demand surveys, can provide very-high-resolution imagery at minimal cost for specific days or locations. Integrating these sources would allow dynamic assessments of parking utilization across different times of day and year, thereby improving the robustness of planning and design decisions. Further, YOLO could be deployed using UAVs or other site-specific cameras (AHA & KIDWAI 2025).

While findings are preliminary, they underscore the potential for better data about parking supply and actual demand. The four parking lots in the study areas were centered in the urban core of Salt Lake City, with the highest levels of usage observed in the downtown center. While the selection of these sites may not fully highlight opportunities for land-use transformation or reductions in parking supply, it demonstrates the accuracy of aerial imagery for monitoring parking utilization. This approach may be especially advantageous in suburban contexts, particularly within established communities where growth projections indicate that parking demand is unlikely to rise significantly in the foreseeable future. The statistical findings generated through this analysis can provide urban planners with empirical evidence to present to city councils and inform public planning processes, supporting the case for revisions to municipal codes that promote more efficient and beneficial land use.

Planning and policy guidelines for parking space allocations vary significantly across jurisdictions, both globally and within the United States. In areas with an oversupply of parking, it is essential to reconsider parking requirements and actual utilization for residential and commercial zones. Systematic monitoring of real-world usage, compared against historical policy norms, would enable municipalities to recalibrate these standards, thereby reducing oversupply and unlocking land for higher-value purposes such as housing, green infrastructure, and mixed-use development. For instance, municipalities could use empirically ob-

served occupancy thresholds to revise minimum parking requirements where chronic underutilization is documented. Likewise, persistently low-occupancy sites could be prioritized for redevelopment, shared-parking consolidation, green infrastructure retrofits such as tree canopy expansion, or other context-appropriate transportation uses (CHAMBERLAIN et al. 2025). Moreover, emerging trends – including e-commerce (FENG & FAY 2022), on-demand mobility (KONDOR et al. 2020), and remote or hybrid work (DING 2025) are reshaping traditional models of parking demand. By integrating advanced monitoring techniques with these long-term behavioral shifts, planners can transition from static regulations to evidence-based strategies that align land use with contemporary mobility patterns and sustainability objectives.

5 Conclusion and Outlook

This proof-of-concept study demonstrates the technical feasibility of using AI-based object detection on remotely sensed imagery to monitor parking lot occupancy. While the findings are preliminary, they reveal substantial declines in four parking lot cases between 2018 and 2021, underscoring the potential for dynamic, data-driven approaches to inform urban planning and land-use policy. Improved monitoring could enable municipalities to recalibrate parking requirements, reduce oversupply, and repurpose underutilized land for higher-value uses. Future research should focus on scaling this approach through larger, more representative datasets, integrating multi-temporal imagery, and leveraging complementary technologies such as UAVs and high-resolution commercial satellites to capture fine-grained temporal patterns. These advancements will support evidence-based strategies that align parking supply with evolving mobility trends, sustainability objectives, and improved land-use.

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Integrating Photographic Place Criteria into Digital Place Making Processes: An AI-Assisted Guiding Model for Urban Landscape Revitalization

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Abstract: This study proposes an AI-assisted guiding model for integrating photographic place criteria into digital place making processes in urban landscape revitalization. Building on theories of environmental perception, imageability, and landscape aesthetics, the study conceptualizes Instagrammability not as a transient cultural trend but as a perceptual-aesthetic indicator grounded in spatial qualities. Photographic place criteria were derived from the literature and tested through a CLIP-based multi-label image-text analysis using images of globally Instagrammed urban landscapes. The validated criteria were subsequently applied to a former industrial heritage site, the Pasabahce Glass Factory in Istanbul, using DALL·E based generative image editing to produce multiple design alternatives. The results demonstrate that recurrent spatial qualities such as geometric clarity, lighting, dominant patterns, and architectural distinctiveness significantly enhance photographability. The proposed model guides designers and planners in digital placemaking processes while emphasizing ethical considerations, participatory integration, and spatial sustainability.

Keywords: Photographic place, digital place making, CLIP-based visual analysis, DALL·E generative design, urban landscape revitalization

1 Introduction

When LEFEBVRE's approach (1991), which emphasizes that space is socially produced, is considered together with CASTELLS' (2010) conceptualization of digital networks as generating a new spatial form the "space of flows", it becomes evident that digital communication technologies have transformed the ways in which space is perceived, represented, and experienced. The widespread use of smartphones and the rise of photographic social media platforms (particularly Instagram) have reshaped individuals' relationships with urban environments through both spatial practices and digital representations (HIGHFIELD & LEAVER 2016, URRY & LARSEN 2011). On photographic social media platforms, this relationship becomes interactive through features such as photographing, sharing, liking, and re-sharing images of places, which mediate new forms of engagement with the urban environment (BARASCH et al. 2016, OELDORF-HIRSCH & SUNDAR 2016). Instagram's visual editing tools and algorithmic recommendation systems make certain urban focal points more visible, enabling compositions deemed "worthy of being seen" to circulate rapidly and become part of a popular visual network (MANOVICH 2017). This dynamic demonstrates that the meaning and value of place are produced not only through physical experience but also through metrics of digital visibility, shareability, and interaction (HIGHFIELD & LEAVER 2016, ROSE & TOLIA-KELLY 2012, URRY & LARSEN 2011). In this context, "Instagrammability" has emerged as a contemporary conceptual framework that refers to places that are aesthetically striking, photographable, and suitable for social media engagement.

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City governments, tourism authorities, and cultural production sectors institutionalize this visibility through "Instagrammable places" lists, urban walking routes, and visual representation oriented urban marketing strategies (IGLESIAS-SÁNCHEZ et al. 2020, RICHARDS 2020). Thus, public spaces and tourist destinations come to be evaluated not only for their functional or historical qualities but also for their representational capacity within the digital ecosystem. This shift requires a reconsideration of the place making approach, which has long been discussed in the literature. When RELPH's (1976) distinction between space and place, TUAN's (1977) explanation that place acquires meaning through lived experience, and SEAMON's (2014) account of place as produced through users' bodily routines and interactional practices are considered together, place making does not regard place as only a matter of physical design; rather, it conceptualizes it as a formation that becomes "place" through processes of attachment, relationality, and shared meaning making. Within this process, the revitalization of urban areas that have lost their appeal or experienced a loss of identity is pursued through social and cultural layers of engagement. However, under contemporary digital conditions, the construction of "place" increasingly occurs through online interactions, digital traces, and social media representations. For this reason, the concept of digital place making provides a more comprehensive framework in which digital technologies are positioned as active components in the production of place attachment and place identity.

Digital place making aims to enhance spatial perception, diversify experiential engagement, and expand participatory processes through tools such as augmented reality (AR), virtual reality (VR), data visualization, and AI-assisted visual analytics. In this regard, this study proposes a research design that does not reduce the phenomenon of Instagrammability to a matter of popular culture, but rather positions it as a perceptual-aesthetic indicator within environmental psychology. The central premise is that the recurrent perceptual, imageable, and aesthetic qualities observed in photographable places can be identified and systematized through artificial intelligence tools, and that these qualities can then be translated into a guiding model capable of informing design decisions within digital place making processes.

The aim of this study is to test photographic place criteria derived from the perceptual, imageable, and aesthetic characteristics of the environment discussed in the literature (KAPLAN et al. 1989, LANG 1987, LYNCH 2010, NASAR 1989), using an AI-assisted analytical tool, and to develop a guiding model that can inform urban design and revitalization processes within the context of digital place making. The model is intended to serve as a practical decision-support tool for designers, planners, and local authorities at both the product level (design alternatives) and the process level (participation and communication).

2 Methodology

2.1 Identification of Photographic Place Criteria

In the process of identifying the criteria referred to as 'photographic place criteria', the first stage examined attributes emphasized in the literature on environmental perception, landscape aesthetics, and imageability that foreground place in terms of perception, aesthetics, and imaginal quality.

LANG (1987) summarizes the fundamental principles that should be considered in spatial organization to achieve perceptual coherence. Accordingly, elements located in close proximity tend to be perceived together; components sharing similar characteristics are perceived as a group; the mind completes missing parts to form a coherent whole; continuous repetitions are perceived as a single entity; perceptual impact increases with scale; and as symmetry increases, the perceptual strength of objects is enhanced. LYNCH (2010) summarizes the formal qualities that enable urban landscape elements to be relationally structured and perceptually legible. Accordingly, an element should be distinguishable from its surroundings, possess a clearly perceivable form, and exhibit continuity. The dominance of certain elements in terms of scale or intensity, the clear legibility of nodes and connections, and the support of perception through directional differences are considered critical. In addition, visibility and depth, the perception of movement, temporally recurring patterns, and the names and meanings attributed to elements are identified as key components that strengthen the spatial image. KAPLAN et al. (1989) synthesize research on landscape quality and preference by identifying four fundamental attributes that shape landscape preferences. Accordingly, people tend to favour landscapes that are composed of coherent and orderly elements, offer visual diversity, are easy to read and support wayfinding, and at the same time evoke curiosity and encourage exploration. NASAR (1989), in his research offering design recommendations aimed at enhancing the visual quality of urban environments, argues that priority should be given to establishing a legible spatial structure composed of paths, edges, districts, nodes, and landmarks. These elements should be strengthened in terms of visibility, contrast, and meaning. In line with these recommendations, the attributes that foreground place in terms of perception, aesthetics, and imageability were further elaborated and operationalized as photographic place criteria (Figure 1), enabling their testing through an image-to-text approach. Criteria such as the meaning or symbolic value of a place were not included in the list, as they vary from person to person and couldn't be physically tested.

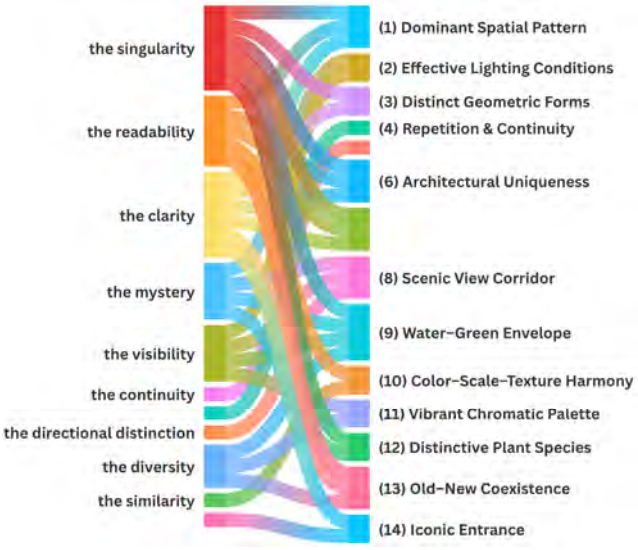

Fig. 1: Photographic place criteria developed by elaborating the criteria obtained from the literature research

2.2 Testing Photographic Place Criteria through CLIP-Based Multi-Label Visual Content Analysis

Photographic place criteria developed by elaborating the criteria obtained from the literature, were tested using 100 images through an image-to-text approach employing the CLIP (Contrastive Language-Image Pre-training) model in a Python (Google Colab) environment. The images used to test the photographic place criteria were randomly selected from images obtained by searching for the names of the world's most Instagrammed urban landscapes via the visual search function on the royalty free image platform (pexels.com), with 10 images selected for each urban landscape (Figure 2).

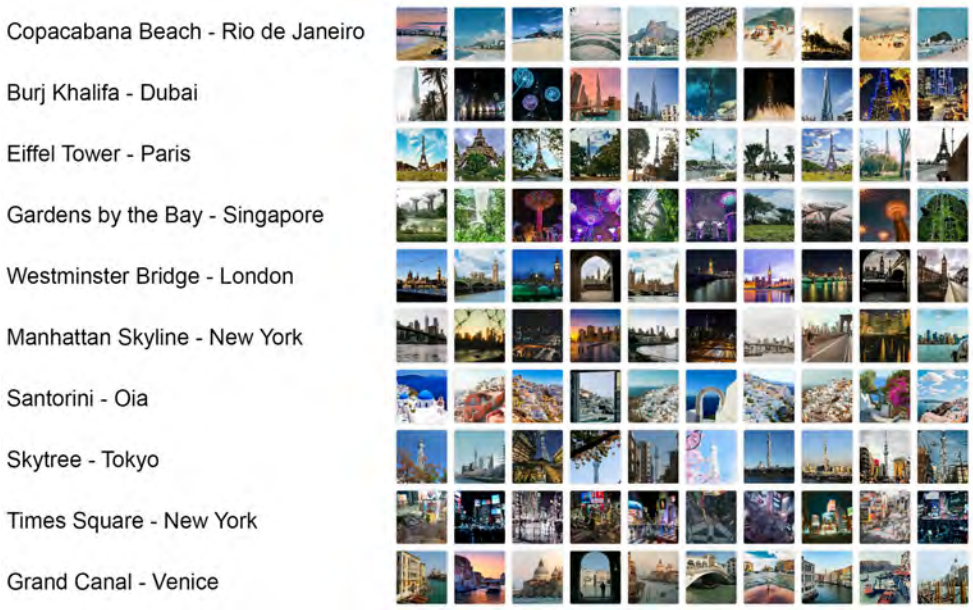

Fig. 2: 10 images from each of the world's most Instagrammed urban landscapes

The CLIP model does not produce the relationship between images and textual concepts as probabilistic outputs, but rather as measures of representational similarity. Due to this structural characteristic, instead of relying on a single threshold when testing the representation of photographic place criteria within the images, three complementary thresholds were applied simultaneously. The absolute threshold (MIN_ABS) indicates that any criterion scoring below this value is considered non-meaningful, thereby eliminating very low or random similarities. The relative threshold (MIN_REL) requires a criterion to reach at least a specified percentage of the strongest criterion score, allowing for comparative strength adjustment among criteria within each image. The percentile threshold (MIN_PCTL) determines the top percentage of scores within each image that are taken into account. Accordingly, the threshold values used in the CLIP-based visual content analysis were set as MIN_ABS = 0.25, MIN_REL = 0.65, and MIN_PCTL = 0.88. The capacity of CLIP to operate across visual and textual embedding spaces enabled the perceptual and aesthetic qualities present in the

images to be matched with corresponding textual descriptors. In Table 1, the representational strength, max strength and recurrence frequency of each criterion were evaluated.

Table 1: Evaluation of CLIP-based multi-label visual content analysis

Criterion ID	Criterion Label	Recurrence Frequency (n)	Mean Representational Strength	Max Strength
1	Dominant Spatial Pattern	17	0.257	0.273
2	Effective Lighting Conditions	32	0.263	0.283
3	Distinct Geometric Forms	32	0.262	0.279
4	Repetition & Continuity	1	0.267	0.267
5	Symmetry & Balance	12	0.263	0.278
6	Architectural Uniqueness	18	0.263	0.277
7	Street Art Expression & Public Art Installations	1	0.295	0.295
8	Scenic View Corridor	4	0.261	0.265
9	Water-Green Envelope	6	0.272	0.298
10	Colour-Scale-Texture Harmony	–	–	–
11	Vibrant Chromatic Palette	1	0.255	0.255
12	Distinctive Plant Species	6	0.271	0.291
13	Old-New Coexistence	1	0.271	0.271
14	Iconic Entrance	2	0.275	0.282

CLIP based image-text matching indicates that an emphasis on geometric form consistently stands out in photographable urban landscapes. Lighting conditions (both natural and artificial) enhance perceptual clarity through shadow-light contrast and improved surface legibility. Distinct architectural components increase the ‘monumental’ effect of a scene; this effect further elevates visual appeal when combined with depth of field and a clearly defined compositional centre. The prominence of surface patterns and symmetry have been identified as qualities that strengthen focal attention. In contrast, other criteria including vegetation diversity, rhythmic repetitions, and artistic elements are represented less frequently in the analysed images; nevertheless, in scenes where they are present, these elements function as ‘secondary enriching’ qualities that support photographability. The Colour-Scale-Texture Harmony criterion, however, was found to be unrepresented in the analysed images.

2.3 Producing Multiple Design Alternatives for Urban Landscape Revitalization Site through DALL·E-Based Generative Image Editing

The Pasabahce Glass Factory in Istanbul was selected as a potential urban landscape revitalization site. Hosting Türkiye’s first glass production facility, the site began operations in 1935 and continued production until 2002. With the zoning plans approved in 1983, the site was designated for ‘tourism facility’ use. However, numerous institutions have advocated for the site’s conservation through a project that would recognize and preserve it as an example of industrial cultural heritage. In this context, to generate design alternatives, the existing con-

dition of the Pasabahce Glass Factory site was represented using image obtained from Google Street View (Figure 3). The photographic place criteria validated in the first stage were subsequently applied to these images using DALL·E's generative image editing tool developed by OpenAI, resulting in multiple design alternatives for the site.

Fig. 3: The existing condition of the Pasabahce Glass Factory site

During the generation of alternative designs, three distinct design proposals were produced by distributing, in a balanced manner, the elements highlighted in Table 1, together with the 'secondary enriching' qualities that support photographability, resulting in three designs distinguished by different dominant criteria. In the alternative designs generated using DALL·E in accordance with the photographic place criteria, considerations drawn from the place-making literature – such as user experience, place identity, and the potential for social interaction – were also taken into account.

In generating the first design alternative (Figure 4), the following prompts were provided to DALL·E's generative image editing tool: the design should feature dominant patterns, incorporate distinctive architecture combining old and new forms, include a corridor gateway opening toward the landscape, reflect the site's former glass factory identity, and accommodate seating and walking uses.

Fig. 4: 1st Design

In generating the second design alternative (Figure 5), the following prompts were provided to DALL·E's generative image editing tool: the design should incorporate effective lighting conditions, distinctive plant species, and an iconic entrance, include public art installation, include water elements; reflect the site's former glass factory identity, and accommodate seating and walking uses.

Fig. 5: 2nd Design

In generating the final design alternative (Figure 6), the following prompts were provided to DALL·E's generative image editing tool: the design should feature distinct geometric forms, be surrounded by multi-coloured planting elements, emphasize symmetry and balance, incorporate public art installations and street art expressions; reflect the site's former glass factory identity, and accommodate seating and walking uses.

Fig. 6: 3rd Design

The generative editing experiments conducted on the sample site enabled the concretization of the criteria. Interventions such as emphasizing spatial patterns, positioning a strong 'iconic' element at the compositional centre, clarifying axis and symmetry relationships at spatial intersections, and employing lighting strategies specific to evening conditions increased the site's photographability potential. These findings demonstrate that photographic place criteria do not merely function as an analytical classification, but also serve as effective design inputs that facilitate the generation of new design alternatives. The findings demonstrate that, through DALL·E-based generative edits, photographic place criteria can be operationalized into a concrete guiding model that directly informs design decisions. In this way, the model supports designers and planners in digital placemaking processes while simultaneously facilitating visual, accessible communication with local stakeholders.

3 Discussion

The findings indicate that Instagrammability cannot be explained only through the temporary trends of popular culture; rather, it is grounded in a consistent set of spatial qualities closely tied to perceptual and aesthetic principles. This study argues for approaching Instagrammability as a design strategy within place making: the deliberate application of these criteria can generate visual focal points and experiential richness in urban landscapes.

However, the use of AI-assisted generative visual editing tools in historical and industrial heritage sites should be critically evaluated not only in terms of aesthetic performance, but

also with regard to spatial memory and the spirit of place. Although the prompts provided to DALL·E in this study explicitly emphasized reflecting the site's former glass factory identity, it is evident that AI systems do not correspond to subjects capable of contextually internalizing historical knowledge. This condition entails the risk that, within digital place-making processes, photographability may be reduced to a superficial visual backdrop rather than establishing a meaningful dialogue with the historical layers of a place. Therefore, it is insufficient for the generated visuals to be merely Instagrammable; they must also engage interpretively with the site's past production practices and collective memory. Otherwise, historical and industrial heritage sites risk being transformed into digitally optimized 'consumable images' for online platforms. In this context, AI-assisted visual production tools should be regarded not as systems that automatically represent the spirit of place, but as instruments that necessitate interpretive and curatorial interventions by designers, planners, and local stakeholders.

In addition, the social and ethical dimensions of photographability must also be taken into consideration. Excessive popularization of particular urban landscapes may lead to issues such as visitor congestion, noise, waste production, and pressure on local everyday life. To mitigate these risks, the guiding model proposed by this study should be integrated with participatory processes, ensuring that design principles remain aligned with the daily practices, needs, and expectations of local communities. In this way, photographic appeal can be managed without diminishing urban quality of life or compromising spatial equity.

4 Conclusion and Future Directions

The findings of this study show that photographable urban landscapes are shaped by perceptual and aesthetic principles such as form, rhythm, pattern, and light, and that the clarity of distinctive architectural elements and compositional centres enhances visibility. Accordingly, Instagrammability is not only a matter of momentary visual appeal, but is also fundamentally related to spatial perception and imageability. The proposed guiding model enables the strategic integration of photographic place criteria into digital place making processes, offering a practical, transparent, and pluralistic framework for revitalizing public spaces, strengthening place identity, and enhancing the quality of urban experience. In this way, the urban landscape is reconceptualized in the digital age as both a physical and a mediatic field of experience, where design decisions can be more closely aligned with users' perceptual preferences.

The limitations of this study include: the analysis being restricted to 10 photographic urban landscapes and a total of 100 images; the CLIP model not always capturing abstract or symbolic spatial qualities directly; and the generative design outputs not automatically accounting for political, economic, or cultural conditions embedded in local contexts. In addition, the proposed guiding model should not direct designers toward an approach focused solely on visual appeal; rather, it should be considered in conjunction with analytical data such as microclimatic assessments, functional use analyses, and user comfort considerations. Indeed, a place that appears visually attractive in photographs does not necessarily imply that its physical comfort conditions are consistently adequate.

Future research should focus on expanding the dataset and integrating this guiding model into participatory processes by incorporating local feedback through participatory methods such as VR-based spatial simulation surveys or participatory design workshops that convey local users' experiences, thereby enabling the combined integration of quantitative and qualitative data. Additionally, examining photographic place criteria alongside governance considerations, such as visitor density and spatial carrying capacity, will be critical for developing a sustainable model of digital place making.

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An AI-Assisted Exploratory Approach to Eminönü Coastal Memory

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Abstract: In Eminönü Square, the coastal area has had its place identity gradually eroded and everyday coastal practices weakened due to extensive urban development interventions (1950s-1980s). This study explores how urban interventions influence the visibility of everyday coastal practices along the Eminönü Coast and their relationship with perceptions of collective memory. It frames everyday coastal practices as repetitive spatial performances that shape collective memory. The study used an AI-based object detection and segmentation framework to identify objects and actions in coastal everyday practices. The survey study complemented the analysis by evaluating how their visibility change and affects collective memory. The visual analysis results indicate that the visibility of coastal practices remained high until the 1970s, then declined in the 1980s. This tendency is largely supported by the survey responses, as indicated by statistical test results. Participants also reported a stronger evocation of collective memory in the earlier images (1950-1970). The findings suggest that urbanization processes havecontributed to the decay in everyday coastal practices and collective memory in Eminönü. The study is limited by differences in quality, small sample size, and the photographic conditions of archival images which affect object detection and segmentation algorithms. It adopts an exploratory approach, using quantified visual visibility as a proxy rather than a direct measure. The survey extends the empirical scope by integrating perceptual data with visual indicators. This study contributes to research on place memory by analyzing spatial everyday practices using AI-assisted visual analysis and user perception evaluations.

Keywords: Historic urban places, collective memory, everyday coastal practices, object recognition, image segmentation.

1 Introduction

Place refers to an abstract location whose meaning derives from environmental, spatial, and experiential characteristics (NORBERT-SCHULZ 1980). As integral parts of existence, places host activities, experiences, and memories. They therefore function not only as a physical setting but also a lived and meaningful environment that mediates the relationship between humans and place. Throughout everyday interaction, individuals develop sensory and experiential connections with the place they inhabit. However, with modern urbanization, the connection to the natural environment has weakened, and identification has increasingly shifted toward the built environment, such as streets and houses (NORBERT-SCHULZ 1980). In parallel, CASEY (2000) draws on the memory- place relationship, arguing that a living memory establishes a direct connection with place. Memory is supported by place and therefore, it is inherently place-oriented (CASEY 2000). Place memory depends on people's ability to connect with both built and natural environments, especially in public spaces where shared experiences accumulate over time (CASEY 2000). Reinforcing this connection, BOYER (1994, 31) describes the city as "the collective expression of architecture, the city carries in the weaving and unravelling of its fabric the memory traces of earlier architectural forms, city plans, and public monuments." The form and architecture of the public spaces play pivotal roles as places of memory through the traces embedded in the changing urban landscape,

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streets and squares, landmarks and monuments, and other physical forms of the city (BOYER 1994).

Public spaces are meaningful places with a spirit of place, where memory is shaped, preserved, and sustained through everyday life activities and urban contingencies (HEBBERT 2005, CASEY 2000). Human memory recalls places through the recollection of daily activities and routines conducted in everyday urbanism in public spaces (HEBBERT 2005). Under the pressures of capitalism and modernism, rapid urban transformation has reconfigured the physical environment, as well as place-based activities, and experiences in public spaces, although they function as the stage of collective memory through their physical traces and meanings (BAYRAKTAR 2015, BOYER 1994). According to BAYRAKTAR (2015), the detrimental impacts of this transformation are fractures in urban and collective memory, the erosion of everyday spatial practices and sensory engagement, and the weakening of emotional and experiential connections to past lived experiences.

In Eminönü Square, the modernist planning approach creates ample urban space for the sake of the visual legibility of historical landmarks, resulting in the removal of vernacular urban forms and coastal activities and the fragmentation of collective urban memory (KUBAN 2010). Eminönü Square, located along the waterfront, serves as the case study site as a major historic and memorable public space in Istanbul, transformed through modernization. Through long-term human engagement with maritime activities, crafts, and spatial practices coastal areas generate distinct tangible and intangible heritage (GALILI & ROSEN 2010, WESTERDAHL 1992 and 2007, cited in OUNANIAN et al. 2021). Shared experience, community practices, and collective memory give meaning to the place and contribute to sustain coastal identity (OUNANIAN et al. 2021). The sea becomes a place for embodied interaction owing to everyday coastal activities, including fishing and boating (ISTANBUL PLANNING AGENCY 2026). By establishing daily contact with the sea through everyday coastal activities, the sea becomes a scenic background and an integral part of everyday urbanism (ISTANBUL PLANNING AGENCY 2026).

In this study, the focus is on ritualized everyday coastal practices as a memory carrier in public spaces. Here, ritualized everyday coastal practices refer to recurrent, embodied activities such as fishing and boating that structure collective memory through repetition. According to CARTEU (1984), everyday coastal activities function as spatial performances that reproduce and reinterpret the place through rhythmic repetition. Therefore, the contribution of everyday practices to the lived experience and spirit of place is significant. In Eminönü, coastal practices and everyday coastline encounters have contributed to a shared coastal identity and collective memory of the place. The coastal practices became everyday rituals of mobility, leisure and economy, forming communicative memory of their time. Through visual archives and narratives, they were later transformed into cultural memory; becoming figures of memory that evoke the former coastal atmosphere, as ASSMAN (2008) puts it.

2 Eminönü Square as Memory of Place

Eminönü Square is a historically significant public space on Istanbul's Historical Peninsula, known as a major transportation hub and market area. Its unique coastal image and distinctive identity have made it memorable place of the city. Before urbanization, Eminönü's picturesque coastal atmosphere was shaped by the small boats, modest local shops, and cafes within

the fish markets, which defined the Golden Horn coastline as Balıkpazarı (ISTANBUL ANSIKLOPEDISI 1955). The Balıkpazarı-Yemiş Pier, located along the coastline between Eminönü and Unkapanı, is a vibrant coastal zone that contributes significantly to the identity and economy of the port city (TÜLEK 2016). The narrow streets, dense urban fabric, and a strong relationship between the street and the coast characterize the district (TÜLEK 2016). In addition, maritime-related food storage, trade, and consumption functions also define characteristics of the Balıkpazarı-Yemiş Pier (BELGE 1994, TÜLEK 2016). Besides, daily maritime transportation ranging from small rowboats and dolmush boats to official ferries has contributed to the coastal identity. These characteristics have made the region a place of memory that preserves its coastal identity through everyday economic and social practices.

Under the modernization effect, Eminönü Square, together with Balıkpazarı-Yemiş İskelesi District, underwent a sequence of urban transformations that disrupted its historical, spatial, and coastal identity (KUBAN 1994, GÜL 2020). In the nineteenth century, the urban transformation of the place began with the introduction of maritime and railway transport, and the construction of the Galata Bridge during the Tanzimat Era, which reshaped the area into a vibrant commercial and transportation hub (KUBAN 1994). The spatial interventions began during the Republican period, with the construction of boulevards and open squares in accordance with the Prost Plan Decisions (1936). This construction disregarded the historical urban fabric and weakened its spatial continuity with the waterfront (GÜL 2020, TÜLEK 2016).

The most radical phase of transformation took place during Menderes' era (1950-1960), when extensive demolitions and expropriations around the New Mosque and the Spice Bazaar were carried out to create modern public squares (GÜL 2020). These interventions resulted in the complete demolition of Balıkpazarı District, eliminating its distinctive spatial character and spatial connection between the coast and inner city (Suriçi) (TÜLEK 2016). With the construction of road infrastructure projects such as Kennedy Avenue and the Unkapanı–Eminönü road, the urban fabric was disrupted and the city’s connection to the sea severed. As a result, the historic fabric of Fish Market disappeared within the loss of coastal culture (KUBAN 1994). By the 1980s, the coastal improvement and beautification projects removed the last remaining parts of the Yemiş İskelesi (TÜLEK 2016). These developments transformed Eminönü into a traffic-dominated node, where spatial memory, cultural identity, and lived experiences weakened (KUBAN 1994). Overall, the gradual removal and relocation of the fish market led to the loss of its former picturesque character and vibrancy. These qualities persist today primarily within the city's collective memory (BELGE 1994).

Alongside these spatial transformations, vernacular watercraft gradually declined. The boats were used for fishing and informal maritime mobility, known as dolmush boats, until the 1970s, when land-based transportation investments intensified, and the Bosphorus Bridge was completed in 1973. This decline weakened everyday coastal engagement and historic coastal identity. Today, the coastal identity has changed in ways that have erased the distinctive atmosphere in which coastal practices were performed. In this regard, this study aims to explore the memory of a place through the weakening of the visibility of everyday practices.

3 Methodology

The focus of the study is on how urban interventions in the Eminönü Coast altered the visual dominance of everyday coastal practices, namely boating and fishing activities, through visual analysis. As an exploratory study, this research is grounded in visual data analysis and supported by a comparative survey evaluation. A considerable number of studies have increasingly adopted semantic image segmentation to extract qualities and integrate with subjective perception. Several reference studies have examined the relationship between visual features and human perception. MA et al (2021) combine semantic segmentation with subjective perception evaluations and analyze how streetscape qualities affect human perception. CAVALCANTE et al. (2014) focus on the relationship between segmented visual features and perceived visual complexity.

In this research, the Recognize Anything Model (RAM) forms part of an image tagging and segmentation pipeline The model brings objects related to coastal practices into the analysis by identifying them, linking them to tag-based colors, and calculating their spatial area values (ZHANG et al. 2023). RAM is a vision-based model that performs multi-label object recognition with explicit vocabulary generalization capabilities with zero error margin (ZHANG et al. 2023). When combined with localization and segmentation models, RAM provides a robust analysis pipeline that sequentially performs object recognition, localization, and segmentation (ZHANG et al. 2023).

This study leverages the REPLICATE (2025) Platform. As a cloud-based platform, REPLICATE (2025) provides users to access and develop open-source machine learning models for specific computational tasks. On the Replicate platform, this study uses the RAM-Grounded SAM model for tagging and segmenting objects in the image (IDEA-RESEARCH 2025). The model enables recognition, color-coded tagging, localization, and boundary delineation of the objects in the images. In this study, the analysis includes only objects representing coastal practices, such as fishing and watercraft elements. All tagging and segmentation tasks were generated automatically by the model from the archive images. Archival photographs from ESKI İSTANBUL (2026) provide the basis for the visual archive used in the research. According to CONNERTON (1989), visual materials are inscribing practices that preserve information beyond direct human presence. The dataset, therefore, includes five distinct images for each decadal period, for a total of 20 images.

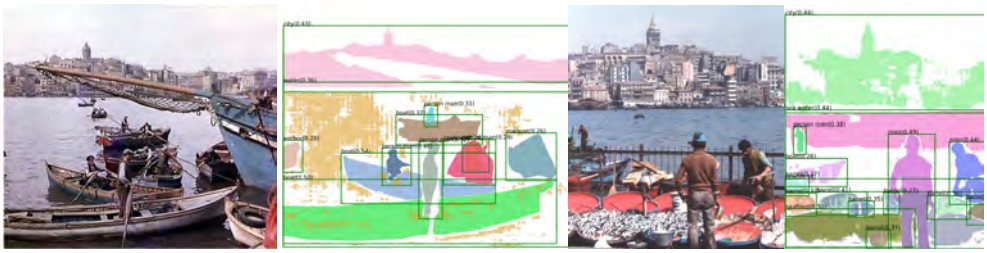

Fig. 1: Original and segmented archival images (RÖSSING 1961, GOTOU 1976, cited in ESKI İSTANBUL 2026)

Drawing on ASSMAN & CZAPLICKA's (1995) emphasis on continuity of rituals as memory carriers through repetition and duration, the study approaches repetition as a condition that produces spatial visibility. It measures the spatial density of the ritualized coastal practices as its spatial trace. Density is computed as the sum of the normalized areas of detected coastal practice objects relative to the image frame. In Equation (Eq. 1), S_{cp} denotes the bounding-box area occupied by the coastal practices *cp*, S total represents the total object area of the image measured by the bounding box, and M refers to the set of coastal practices classes in the analysis.

$$Density_{cp} = \frac{\sum_{cp \in M} S_{cp}}{S_{total}} \quad (1)$$

To examine how urban interventions influence the visibility of coastal practices and place memory, the research conducted a survey with ten participants, including both visitors and domain experts. Participants compared paired historical photographs using a forced-choice scale ranging from −2 to +2. The survey investigates to what extent urban interventions affected the visibility of the coastal practices and how these practices contribute to collective memory and sense of place. The analysis applies directional Wilcoxon signed-rank tests to compare participants' evaluation scores because the survey data have an ordinal structure and the sample size remains small. The Wilcoxon Signed-Rank Test is applied when the same participants assess the same criteria in two paired conditions (PALLANT 2015). It ranks the differences between the two evaluations in different times and determines whether the median difference is statistically significant (PALLANT 2015).

4 Results and Conclusion

The visual analysis first segmented the images in the visual archive into objects, then categorized them by coastal practices, and calculated their density. The dataset classifies archival photos into ten-year categories. Objects in the images were automatically detected and tagged using a segmentation-based algorithm that calculated the pixel area occupied by each identified object (Fig. 1). The study focuses only on coastal practices, categorized as boat-related and fishing-related. Due to sample limitations, the asymmetrical distribution of values, and the possibility of outliers depending on the shooting angle and location in some photographs, median values were used in the evaluation, as shown in Figure 2.

The interpretation of the findings combines segmentation-based graphical analysis with the survey results. The line graph (Fig. 2) shows that coastal practices generally increased until the 1970s, then declined significantly between the 1970s and 1980s. The findings indicated that the reduced use of maritime transportation contributed to the decline of boating as an everyday coastal activity. Furthermore, the visibility of coastal activities along the coastline changed with the redevelopment of Eminönü Coastal Square in the 1980s. The decline in fishing activities can be attributed particularly to the removal of the Balıkpazarı-Yemiş Pier and the relocation of the Fish Market in the 1950s. This relocation also disrupted the spatial continuity of fishing-related activities. Overall, the findings show that coastal-practice visibility reaches its highest level in the 1970s.

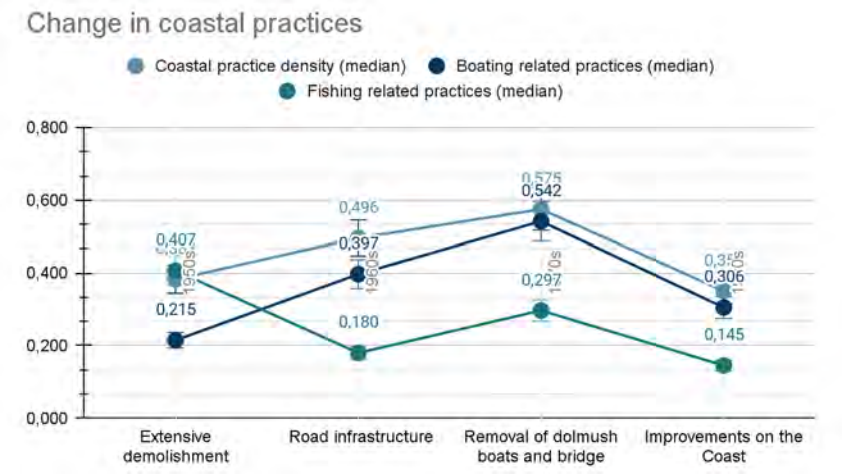

Fig. 2: Median density values of coastal practices over ten-year periods

Table 1: Statistical test results

Measures	**Coastal practices visibility**				**Evocation of collective memory**			
Period	**n**	**T**	**Exact p**	**Result**	**n**	**T**	**Exact p**	**Result**
1950-1960 (Q1 boating practices)	7	0 $R^+>R^-$	0.0078	**Significant**	8	0 $R^+>R^-$	0.0039	**Significant**
1950-1960 (Q2 fishing practices)	7	10.5 $R^+>R^-$	≈0.28	Not significant	6	9 $R^->R^+$	0.66	Not significant
1960-1970 (Q3 boating practices)	9	10.5 $R^+>R^-$	0.0586	**Borderline**	7	9.5 $R^+>R^-$	0.27	Not significant
1960-1970 (Q4 fishing practices)	9	9 $R^+>R^-$	0.0586	**Borderline**	7	0 $R^+>R^-$	0.0078	**Significant**
1970-1980 (Q5 fishing practices)	9	9.5 $R^->R^+$	0.0586	**Borderline**	9	16.5 $R^+>R^-$	0.18	Not significant
1970-1980 (Q6 boating practices)	8	18 $R^-=R^+$	0.50	No difference	9	9.5 $R^+>R^-$	0.73	Not significant

To examine whether the tendency arises from the median of the coastal objects, the study formulated a directional hypothesis and conducted a one-tailed Wilcoxon signed-rank test on survey evaluations. The survey findings largely confirm the graphical results. In their assessments over ten-year periods, participants reported significant differences in the visibility of coastal practices: a gradual increase from the 1950s to the 1970s, followed by a decrease

from the 1970s to the 1980s. In the survey, directional Wilcoxon signed-rank analyses revealed a statistically significant difference for these decades (1950-1980), indicating a perceptual differentiation in coastal-practice intensity (Tab. 1). Moreover, participants reported a stronger collective memory perception in earlier decades in both the 1950-1960 and 1960-1970 periods (Tab. 1). As a result, coastal identity and place memory weaken due to urbanization efforts, as demonstrated by participants' recall.

Lastly, participants assess alternative coastal scenarios generated through AI models trained on archival images. The training process used Low-Rank Adaptation (LoRA), and changes in the LoRA weight coefficients generated multiple visual variations. In the survey, 40% of respondents selected Image B for its stronger visual cues of everyday coastal practices, while 30% linked Image C to a stronger sense of collective place memory (Fig. 3). Image B was produced using a model fine-tuned on 1960s' images, with moderate LoRA weight (0.6), whereas Image C was generated using a model trained on 1950s'images with a higher LoRA weight (0.8). Their prompts combined an existing image of Eminönü with a textual description of its historical atmosphere. Participants selected images with more visible coastal practices and more evocations of the place memory and the sense of place.

Image B Image C

Fig. 3: Generative AI produced images

Several limitations influence the interpretation of the findings. The small sample size and differences in the quality and resolution of archival images affect the performance and reliability of object recognition and segmentation models. These conditions can also influence the results. Moreover, object detection and segmentation outcomes show alteration under different visual conditions inherent to photographic production, including framing, camera distance, angle of capture, and perspective distortions. Participant feedback further indicated that image quality and limited visibility of the urban silhouette may have influenced their responses. In the survey, the small sample size (10) limits the Wilcoxon test's statistical power and may reduce the likelihood of detecting statistically significant results.

Given the limited number and varying quality of archival images, the numerical results Given the limited number and varying quality of archival images, the numerical results from segmentation should be interpreted as indicative rather than definitive. The analysis uses quantified visual visibility as an indirect sign of coastal practices. Segmentation results reveal relative visual patterns but also reflect the production conditions of the photographs. Because of these constraints, the interpretation focuses on general trends rather than specific practice

density measures. A perception-based survey complements the visual analysis and adds an empirical perspective to the interpretation.

The study contributes to research on place memory by examining everyday practices through AI-assisted visual analysis of archival images, supported by user-perception assessments. Computational analysis highlights patterns in the visibility of spatial practices across decades, while survey responses connect these patterns to participants' perceptions of collective memory.

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Artificial Intelligence-Assisted Ideation and Digital Fabrication for Adaptive Living Shoreline Infrastructure

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Abstract: Living shorelines offer adaptive, ecological alternatives to grey coastal infrastructure, yet translating ecological intent into fabricable 3D forms remains a key bottleneck. This study presents an AI-assisted concept-to-prototype workflow tested in a landscape architecture ecology course, integrating generative AI for 2D ideation, AI-driven 3D modelling, and digital fabrication. Qualitative thematic analysis of 52 student reflections indicates that AI significantly accelerates design exploration and prototyping while requiring careful prompt construction, ecological verification, and human oversight. The findings demonstrate that AI functions as a supportive and mediating tool, positioning designers as essential "human-in-the-loop" collaborators and reinforcing the importance of ecological expertise and ethical responsibility in design.

Keywords: Artificial intelligence, living shorelines, AI-assisted workflow, digital fabrication

1 Introduction

One of the significant obstacles for modern landscape architecture is the escalating impact of climate change on coastal regions (IPCC 2022, WANG & ZHANG 2023). Rising sea levels, coupled with the increased frequency of storm surge and erosion, threaten both human settlements and critical ecosystems (TEBALDI et al. 2021). Although grey engineering-based solutions (e. g., concrete seawalls) have been implemented to reduce coastal hazards, they are often costly, ecologically disruptive, and lack the flexibility required for dynamic environments (TIWARI et al. 2025). It is necessary to develop cost-effective strategies that provide tangible ecological benefits for climate adaptation.

Living shorelines have gained increasing attention for their ability to build upon natural features and adaptive infrastructure to reduce erosion, buffer wave energy, and sustain coastal ecosystems (MORRIS et al. 2022, SLOYE et al. 2025). For example, marsh plants, sediment nourishment, shellfish reefs, and hybrid "soft" infrastructure provide more resilient alternatives. Meanwhile, the field of digital landscape architecture has evolved from basic visualization and analysis into a comprehensive pipeline linking geospatial data, simulation, artificial intelligence (AI), and design interventions (CLINGEN & BOOZ 2025, HUANG 2025, VOGLER et al. 2025).

In this broader evolution, a gap persists between high-level environmental analysis and the design of small-to-medium-scale physical elements, such as reef modules and ecological concrete units, that constitute living shoreline systems. Many of these components are currently manufactured in standardized forms, often overlooking local hydrodynamics, habitat goals, or the potential for community co-design. Industry precedents, such as Natrx's modular living shoreline system, demonstrate how data-driven design and repeatable units can form flexible coastal protection networks (NATRX 2025). However, the design workflow that translates

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ecological performance goals to manufacturable and deployable 3D models remains a major bottleneck for both practitioners and students. Therefore, this research addresses a central question: How can designers efficiently explore the vast solution space of complex forms, embed ecological intelligence, and validate designs through physical prototypes?

This research builds on prior work at the intersection of digital landscape architecture and coastal resilience. It showcases an AI-assisted concept-to-prototype workflow which links conceptual sketching, generative visualization, 3D modelling, and digital fabrication. The process was piloted within a third-year Bachelor of Landscape Architecture (BLA) advanced ecology course focused on "adaptive infrastructure for living shorelines." Final outputs included conceptual posters, physical 3D models, and animated videos to demonstrate how adaptive infrastructure can conceptually address erosion and storm surge challenges while enhancing ecological performance climate-vulnerable coastal environments.

The findings suggest that an AI-assisted design workflow significantly reduces the time required for model generation. However, AI remains a supportive and mediating tool and still requires ecological verification and sustained human oversight. The contributions of this study include integrating Large Language Models (LLMs)-based prompting, generative image tools, AI-driven 3D modelling, and physical fabrication into a continuous workflow rather than focusing solely on visualization. This study also situates AI experimentation within the ecological framework of living shoreline infrastructure, which embeds habitat logic and modular aggregation into each stage. Since this study restricted AI use during the initial sketch phase, it establishes a pedagogical control that clarifies AI's cognitive and translational roles in later phases. The integration of generative AI for ideation with 3D printing for fabrication represents a transformative paradigm for landscape architecture education.

2 AI-Assisted Design Workflow Methods

The core of this research is a five-stage workflow that guides students from abstract problems to physical prototypes (Figure 1). This framework was implemented in the Resilience Lab at the College of Environment and Design, the University of Georgia (UGA). Using a project as a detailed case study, we documented the complete workflow from hand-drawn sketches to fabricated physical prototypes. This process was tested in the third-year BLA's Advanced Ecology course, where focused on designing adaptive infrastructure for living shorelines. A cohort of 27 students participated in the study and submitted 52 reflections (two reflections per student, with one submission missing).

The design workflow comprised the following stages: (1) Conceptual Hand-Drawing: Students developed initial modular shoreline unit concepts through traditional sketching, focusing on biological and structural forms. (2) AI-Assisted 2D Concept Generation: Based on their manual sketches, students employed iterative prompting in generative AI tools (such as Adobe Firefly) to refine and visualize their modular concepts; (3) AI-Assisted 3D Modelling: Students utilized AI-powered modelling platforms (such as Tripo AI) to translate their 2D concept images into fabricable 3D digital models; (4) Digital Fabrication (3D printing): Physical prototypes were produced using 3D printers, including the Bambu Lab H2D printer and Original Prusa MK4S 3D printers at the Lab; (5) Critical Reflection: At the conclusion of the project, the students submitted qualitative reflections on the AI-assisted workflow in both 2D concept and 3D modelling. We used thematic analysis to analyze the qualitative data.

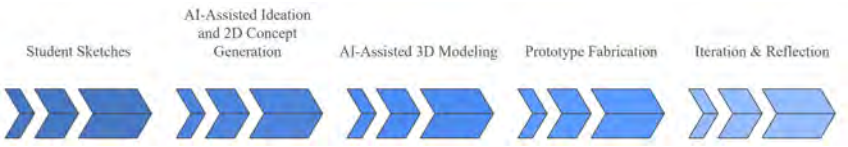

Fig. 1: AI-Assisted Living Shoreline Prototype Workflow

2.1 Student Sketches

In the fall semester of 2025, 27 students spent half of the term establishing a foundational understanding of ecological design principles and living shoreline systems through instructor-led lectures, assigned readings, and guest presentations (e. g., NATRX). Then, each of them developed hand-drawn concepts for adaptive infrastructure, focusing on a "singular modular living shoreline unit." These units were required to be sculptural, repeatable, and capable of both shoreline stabilization and habitat provision for aquatic life. Students submitted three of their most viable and creative concepts (Figure 2). They were not allowed to use external assistance during this initial phase, including search engines or AI tools. This restriction ensured that all concepts were generated independently, based solely on students' existing knowledge and ecological understanding.

2.2 AI-Assisted Ideation and 2D Concept Generation

In the second phase, students independently utilized LLMs to translate their hand-drawn sketches into descriptive prompts (Figure 2). They described the target forms in natural language, iteratively moving from concise prompts to more detailed narratives of form, structure, and ecological function. The refined prompts along with the scanned sketches were then processed through generative AI tools (e. g., Adobe Firefly) (Figure 2). Its purpose was not to replace students' original concepts but to rapidly generate diverse visual iterations rooted in the initial hand-drawn geometry. This AI-assisted ideation stage was indispensable for breaking away from standard forms and exploring complex geometry shapes that are beneficial for biological colonization and wave energy dissipation. This process was similar to other applications in landscape analysis, where models are trained to interpret complex patterns but apply them in a generative, forward-looking manner (CLINGEN & BOOZ 2025). This stage demonstrates how AI shifts early design cognition from visual intuition to semantic precision.

Fig. 2: Student sketches and AI-assisted ideation

2.3 AI-Assisted 3D Digital Modelling

The third stage involved translating the most viable 2D AI-generated concepts into 3D-printable digital models. This is a crucial step in design explanation and refinement, where students played a connecting role between the AI-generated "visions" and the demands of ecological performance. Utilizing AI-driven 3D modelling platforms (e. g., Tripo AI), students were divided into nine groups to develop digital models (two models per group) and embed design logic centred on ecological functions and coastal resilience. This ecological design logic included four components. Students uploaded the final concept images to Tripo AI, which generated volumetric 3D models (e. g., STL file) within minutes, bypassing traditional manual modelling constraints (Figure 3). To prepare for fabrication, the STL files were audited and refined in standard slicing software (e. g., PrusaSlicer). Models were scaled to representative dimensions and prepared for high-fidelity output. The transition from 2D imagery to volumetric modelling exposed a representational gap between visual plausibility and structural feasibility. Finally, while students did not perform hydrodynamic simulations, they were required to justify how specific formal features would conceptually contribute to wave attenuation, promote the recruitment of oysters and vegetation, or facilitate interlocking in modular arrays.

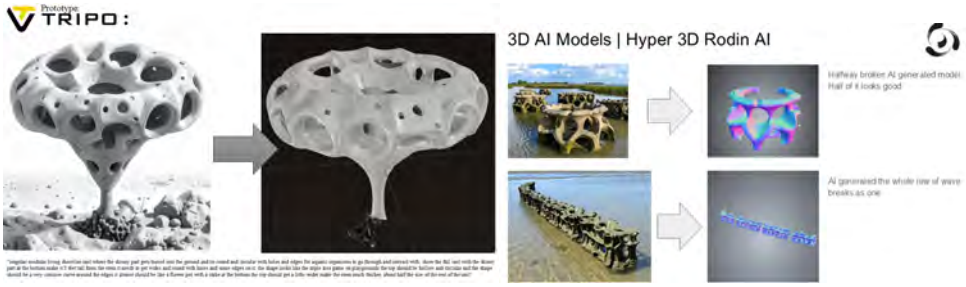

Fig. 3: AI-Assisted 3D digital modelling

2.4 Digital Fabrication & Prototyping

With refined 3D models, the workflow transitioned from virtual design to physical prototyping. Physical prototyping translates the abstract design concepts into tangible forms in order to make them more accessible and comprehensible, particularly for non-expert audiences (WANG & WANG 2023). Students fabricated their designs using 3D printers, including Bambu Lab H2D and Original Prusa MK4S 3D printers in the Resilience Lab. This hands-on prototyping phase exemplified research through making approach. The translation of digital files into a tangible object promptly revealed critical design flaws and fabrication issues, such as inadequate support structures or weak connections. Through iterative cycles of designing, printing, testing, and redesigning, students refined their modular prototypes to improve structural integrity and fabrication efficiency. Common refinement steps included thickening fragile elements, repairing mesh errors, resolving non-manifold geometry, and adjusting overhang angles to ensure printability, underscoring continued human oversight. In professional practice, fabrication restrictions are as important as the design intent. Therefore, this iterative physical testing was essential for developing viable, executable solutions (Figure 4). All prototypes were fabricated using standard polylactic acid (PLA) filament with a

layer height of 0.2 millimetres. A single one-kilogram spool of PLA, priced at 32.99 United States dollars (USD), could produce between one and five or more models, depending on model size and print settings. Overall, material costs were low.

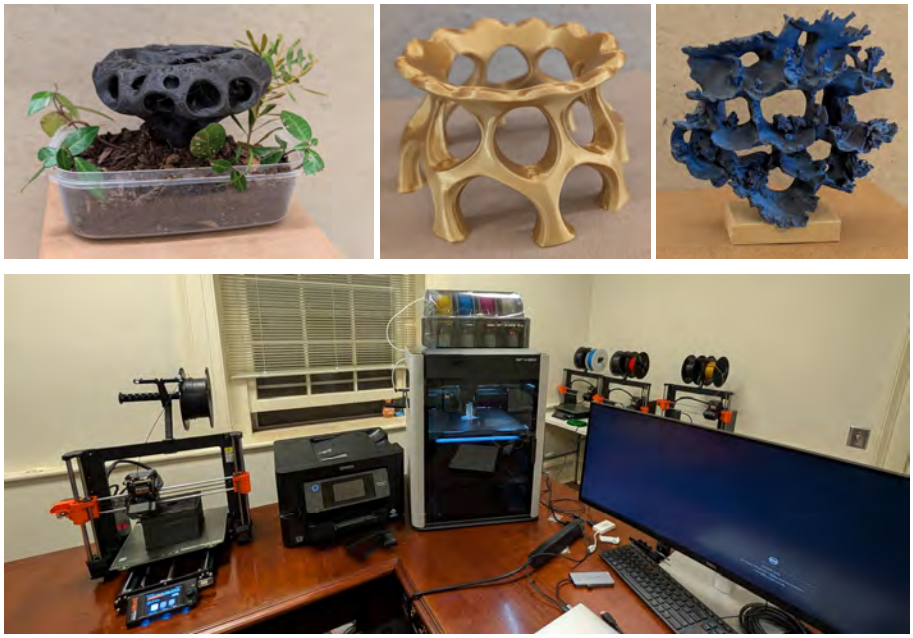

Fig. 4: Printed 3D models and 3D printers

2.5 Reflection and Evaluation

A primary outcome of this study was the evaluation of student reflections and perception. A qualitative thematic analysis was conducted on 52 reflections on AI-assisted concept ideation and 3D modelling submitted by 26 students. This analysis aimed to synthesize student experiences regarding the utility of AI to assist the design process. Following an inductive protocol, reflections were anonymized and iteratively coded. Initial open coding identified recurring concepts related to AI use, ecological reasoning, workflow challenges, and ethics. Codes were then grouped into broader themes through axial coding, resulting in stabilized thematic categories. Coding was conducted by the first author and reviewed through peer discussion with the co-author to strengthen analytical consistency. Themes were finalized when no new categories emerged, and a codebook was developed. The analysis captures pedagogical perception rather than objective performance metrics, but the structured coding process enhances transparency and credibility.

The initial phase of AI-assisted concept ideation transformed the design process from manual sketching to linguistic iteration by LLMs and Generative AIs. There were four dominant themes characterized the student experience and thoughts, including temporal compression, designing through language, the need for ecological verification, and ethical concerns. Most students believed that AI-assisted ideation shortened the timeframe for early design exploration. The rapid generation of visual alternatives enabled students to survey of a broad “design

landscape" in minutes. This speed encouraged non-traditional ideas due to the low cost of iteration. One student reflected, "The main benefits of using AI for concept generation are time, efficiency, and the ability to rapidly explore multiple design directions without the usual limitations of hand drawing or 3D modelling. I didn't have to spend hours sketching or rendering every idea that came to mind; instead, AI could instantly visualize a wide range of concepts, which I could then refine and adjust based on my goals (Student 19 [S19])." A major finding was the realization that AI required linguistic precision. It became a form of design labour for the AI-assisted design workflow. Students emphasized that small changes in wording, such as substituting "artificial reef" with "reef-like form shaped by natural erosion (S7)," produced different visual outcomes. This led to a shift in how students conceptualized design authorship, moving from drawing and modelling toward iterative prompt construction.

Although students reported that AI-generated images introduced forms or spatial ideas they did not initially envision, they were concerned that these AI products focused on visual aesthetics while lacking an inherent understanding of ecological processes and site conditions. As a result, students described a recurring need to verify AI outputs against ecological knowledge. As students noted, "AI can generate shapes and surfaces, but it doesn't understand ecology, culture, or the purpose behind a design (S6)." "I had to constantly verify the outputs with real ecological principles and case studies (S13)." Students also discussed ethical questions regarding AI use, with a focus on originality and authorship. They considered AI as a supportive ideation tool rather than a creative designer. While many acknowledged AI's value for rapid brainstorming and visualization, students argued that authorship resided in human decision-making, including selecting prompts, rejecting outputs, validating ecological logic, and translating concepts into fabricable forms. For instance, "It is tricky ethically… I don't think image generation models are advanced enough to 'do our projects for us,' and even if they were, they shouldn't (S1)."

In reflections on AI-assisted 3D modelling, students consistently described the transition from 2D imagery to 3D geometry as the most challenging and revealing stage of the workflow. In addition to previous themes, cognitive bottleneck emerged another significant theme. While AI-generated images appeared visually convincing, their translation into volumetric form exposed gaps in scale, thickness, structural logic, and spatial completeness. 3D modelling shifted students from aesthetic evaluation to constructive reasoning. As digital models were prepared for 3D printing, students reported a critical shift in their understanding of the design. Forms that appeared plausible on screen often lacked volumetric integrity when materialized (e. g., weak connections). "The software automatically created a 3D version of it, and while it looked impressive at first, the model needed a lot of cleaning up. Some parts didn't make sense structurally; there were problems getting the model to have spaces in between the roots so at first it looked more like a big blob (S9)." Furthermore, 3D printing process revealed physical constraints that AI could not anticipate, such as gravity and fabrication tolerances. This reinforced the role of physical prototyping as a validation step rather than a mere representational exercise. "It also exposed some of the limitations of AI-generated models. Certain forms that looked fine on screen didn't translate well into 3D printing; they were too thin, too fragile, or not structurally sound. These challenges showed me how important it is to bridge digital design with real-world testing (S6)."

3 Discussion

The findings indicate that AI functions as an accelerant and mediator in the design process. In the 2D concept generation phase, AI enables rapid visual ideation. This introduces a shift from intuitive visual thinking to linguistically mediated reasoning. Students learned that AI interprets design intent literally rather than intuitively, which requires precise prompts that are often refined through large language models. Beyond procedural acceleration, the workflow reveals a cognitive shift in ecological design reasoning. Prompt-based iteration externalizes design intent into language. As a result, ecological logic must be articulated explicitly. Although AI occasionally acted as a creative provocateur, it also presented risks of ecological misrepresentation. Therefore, students emphasized the necessity of human oversight to verify ecological credibility. During 3D modelling and prototyping, AI played a translational role, converting images into volumetric geometry. The transition from 2D imagery to 3D form functioned as a critical verification stage, revealing issues of scale, thickness, negative space, and structural feasibility that were obscured in two-dimensional representations. Although AI tools lowered the technical barriers to early prototyping, they lacked an intrinsic understanding of hydrology, habitat connectivity, and material performance.

Regarding ethics and authorship, the study suggests that designers perceive AI as a supportive, translational instrument rather than a creative authority. The retention of authorship is fundamentally tied to human judgment, ecological reasoning, and transparent workflow documentation. The limitations of this research include its reliance on student-authored reflective writing, which captures qualitative perceptions and pedagogical experiences. No hydrodynamic simulations or field validation were conducted. Therefore, performance-related statements reflect design intent rather than empirically tested outcomes.

4 Conclusion and Outlook

Overall, the study demonstrates that AI-assisted 2D ideation and 3D modelling workflows effectively compress the distance between concept and prototype. However, this acceleration intensifies the necessity for human ecological literacy, linguistic precision, spatial reasoning, and ethical responsibility. In the context of living shoreline infrastructure, while AI expands conceptual capacity and accelerates iteration, the translation of ecological intent into resilient, fabricable systems remains fundamentally dependent on human expertise. This is positioning designers as essential “human-in-the-loop” collaborators.

The transition from 2D imagery to 3D geometry emerges as a critical pedagogical moment, where visual imagination is confronted by spatial and material reality. Physical prototyping further grounds this process, reinforcing the limits of automation and the necessity of ecological verification. For landscape architecture education, these findings suggest that AI is most effective when positioned as a mediating tool within a structured concept-to-prototype pipeline. Such workflows can expand students’ capacity to imagine, test, and refine resilient systems while preserving the human expertise required to ensure ecological performance and ethical responsibility. Future research should examine how AI can be responsibly and productively embedded within ecological design processes through advanced simulation, such as linking generative forms with real-time hydrodynamic and habitat-connectivity data. As these tools evolve, the goal remains to embed them critically within the design process, en-

suring that the next generation of landscape architects can navigate the complexities of climate adaptation with both technological fluency and ecological responsibility.

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3D Scanning, Point Clouds and BIM Modeling

Multi-Source Point Cloud Fusion for Accurate Landscape Analysis and Management: A Practice-Oriented Workflow for Urban Parks

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Abstract: Point cloud technologies are promising for digital management of landscape and garden spaces, but single data sources are limited by viewing geometry, occlusion, and accuracy. Using the China Green Expo Park in Nanjing as a case study, this paper compares backpack LiDAR, UAV-borne LiDAR, and oblique photogrammetric point clouds, and develops a multi-source fusion workflow combining unified preprocessing, three-point registration in RealWorks, and voxel-based weighted fusion with down-sampling. Backpack LiDAR best captures understorey and ground detail, UAV LiDAR efficiently represents canopy and roofs, and oblique photogrammetry contributes canopy outlines and texture but has weaker geometric reliability. The fused point cloud markedly improves spatial completeness and consistency, achieving residuals of about 35 mm and an estimated overall accuracy of roughly 2-5 cm after registration and fusion, sufficient for most landscape planning and management tasks.

Keywords: Multi-source point cloud fusion, backpack LiDAR, UAV LiDAR, oblique photogrammetry, geometric accuracy, workflow

1 Introduction

With accelerating urbanisation, landscape and garden spaces are expected to mitigate urban heat, enhance ecosystem services, and improve visual and experiential quality (CHENG et al. 2021). Supporting these goals increasingly relies on reliable 3D spatial information. Point clouds derived from laser scanning and image-based reconstruction can capture detailed terrain, vegetation, and built structures, and are widely used in forestry and urban 3D modelling (HAN 2020). However, in landscape and garden projects, no single point cloud source can simultaneously provide large-area coverage, high geometric accuracy, and fine human-scale detail.

Backpack LiDAR, UAV-borne LiDAR, and oblique photogrammetry each address part of this trade-off: mobile systems are strong for understorey and ground-level features, UAV-borne LiDAR for canopy and roofs at larger scales, and oblique imagery for visually rich models, but each has clear limitations in coverage, penetration, or geometric reliability. In remote sensing and geoinformatics, many fusion approaches have been proposed to combine such datasets, yet most target forest inventory or engineering surveying rather than the practical needs of landscape architecture.

Against this background, the aim of this paper is not to introduce a new fusion algorithm, but to construct and validate a clear, parameter-transparent, and reproducible multi-source point cloud fusion workflow for landscape analysis and management (Fig. 1). Using the China Green Expo Park in Nanjing as a case study, we analyse how three complementary data

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sources can be jointly registered and fused, and how this improves spatial completeness and geometric consistency relative to single-source data. The goal is to offer landscape practitioners an operational pathway for choosing and combining point cloud sources for different project scenarios.

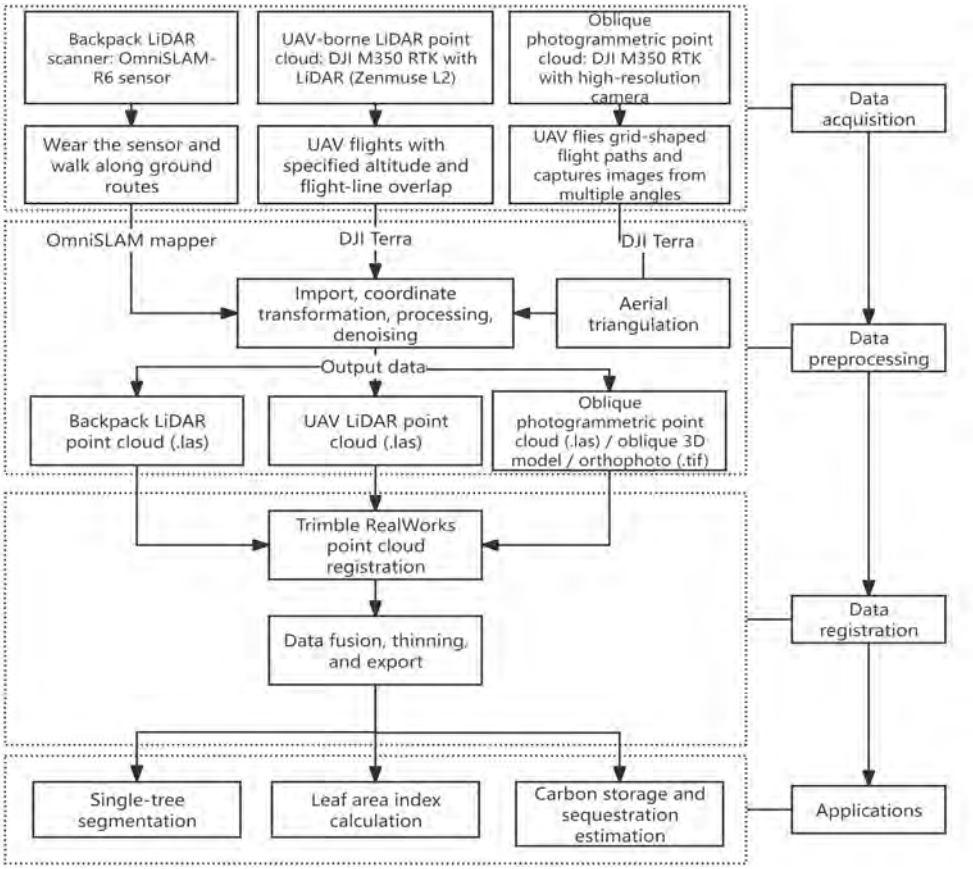

Fig. 1: Multi-source point cloud fusion workflow

2 Study Area and Data Sources

2.1 Study Area and Coordinate System

The study area is the China Green Expo Park in Nanjing, a large urban park with diverse spatial types including dense woodland, open lawns, water bodies, plazas and roads, and multiple landscape structures. Data were collected in May 2024, when vegetation was in a vigorous growing stage, which is favourable for analysing canopy and understorey structures (Fig. 2).

Fig. 2: Comparison between point clouds and current site conditions

During field acquisition, all systems used WGS84 as the operational coordinate framework, combined with ground control points (GCPs). For post-processing and metric analysis, all datasets were transformed into the China Geodetic Coordinate System 2000 (CGCS2000) with a Gauss-Krüger projection, so that both planimetric and height measurements are in metres, avoiding errors associated with distance and area calculations directly in geographic coordinates.

2.2 Acquisition of Three Point Cloud Datasets

Fig. 3: Processed backpack LiDAR point cloud in the study area

The backpack point cloud was collected with a mobile mapping system (OmniSLAM-R6) equipped with a rotating LiDAR sensor. After connecting to a cloud RTK service, the IMU was calibrated in WGS84, and the operator followed planned walking routes covering main roads, plazas, and representative landscape spaces, with an emphasis on understorey and near-ground information. The system recorded LiDAR scans, GNSS/IMU trajectories, and 720° VR images, which are useful for later checking of tree species and site conditions. The

raw data were processed in OmniSLAM Mapper for trajectory smoothing, loop closure optimisation, and block adjustment to generate an initial point cloud. For a study area of about 0.26 km², the processing took roughly 5 hours; depending on computing resources, the data can be merged into a single block or kept as time-based segments (Fig. 3).

UAV LiDAR data were acquired using a DJI Matrice 350 RTK platform with a Zenmuse L2 sensor. Three flight missions were planned to cover the study area, with a flight altitude of about 150 m and 45% track overlap. To balance mapping efficiency and canopy penetration, a repetitive scanning mode was used with a scan angle of about 45°. The Zenmuse L2 supports up to five returns per pulse; in repetitive scanning mode the output rate is about 240 k points/s for single returns and 1,200 k points/s for multiple returns, with a field of view of approximately 70° × 3°. DJI Terra was used to process raw GNSS/IMU and LiDAR data, yielding a WGS84-based point cloud that was then transformed to CGCS2000. Under RTK FIX status at 150 m altitude, the horizontal and vertical accuracy is generally in the 4-5 cm range. The UAV LiDAR covers about 0.82 km², with a density sufficient for structural analysis at 1:500-1:2000 map scales (Fig. 4).

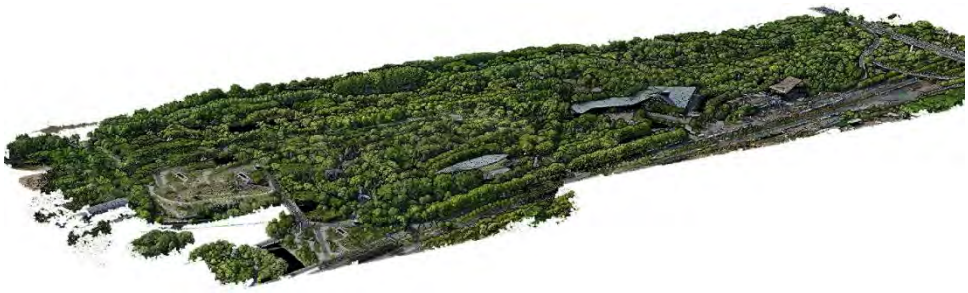

Fig. 4: UAV LiDAR point cloud over the study area

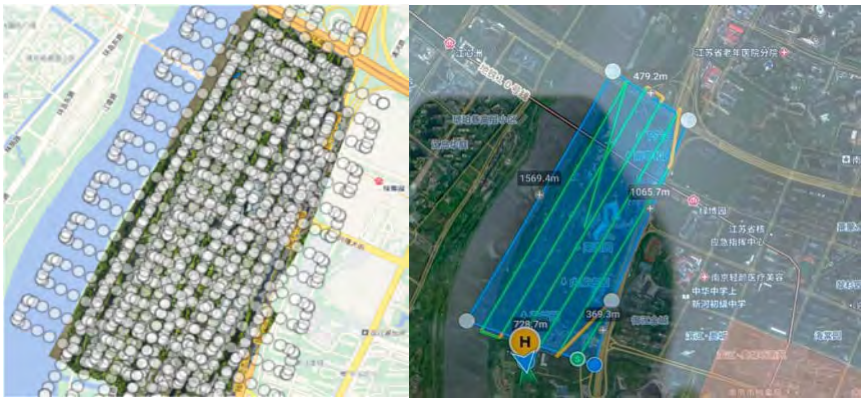

Fig. 5: Camera positions and flight paths

Oblique photogrammetric data were also acquired with the DJI Matrice 350 RTK and a calibrated camera. At 100 m altitude a gridded flight plan with 80% forward and side overlap was flown, yielding 1,374 images. DJI Terra was used for aerial triangulation and dense reconstruction, producing textured 3D models (OBJ/OSGB/B3DM), LAS point clouds, and orthophotos. The root-mean-square reprojection error was about 1.3 pixels, and the GCP RMSE about 0.05 m, indicating reliable overall adjustment. Point clouds are dense and contours crisp in high-texture, unobstructed areas, while water surfaces, low-texture façades, fine branches and leaves, and shadowed areas tend to be sparse or noisy. These characteristics are explicitly considered later in the geometric analysis and fusion weighting (Figs. 5 and 6).

Fig. 6: Oblique photogrammetry 3D model

2.3 Data Preprocessing

The three point cloud datasets followed similar preprocessing steps. First, using GCPs, all three were transformed into the CGCS2000 Gauss-Krüger projection. Statistical outlier removal and height-based filtering were applied to remove obvious floating points and isolated noise. Where needed, ground/non-ground classification was performed on the UAV LiDAR and oblique point clouds to support terrain and vegetation analysis. For large-area datasets, spatial tiling on a regular grid was used to build indexing structures to support block-wise processing during registration and fusion.

3 Multi-Source Point Cloud Registration and Fusion

3.1 Registration Strategy

Given the differences in acquisition modes and error sources, backpack LiDAR was selected as the geometric reference dataset. The backpack point cloud generally has higher local accuracy and better detail for understorey and near-ground structures, and overall consistency after internal adjustment. UAV LiDAR and oblique photogrammetric point clouds were aligned to this reference. The goal of registration was to bring all three point clouds into a common projected coordinate system with “good enough” accuracy for landscape analysis and to avoid obvious misalignment, shearing, or ghosting.

3.2 Alignment in RealWorks

Multi-source registration was carried out primarily in Trimble RealWorks. The backpack, UAV LiDAR, and oblique point clouds were imported together. Using the backpack dataset as reference, three clearly defined geometric points were identified both in the UAV LiDAR and oblique point clouds, e. g., roof corners, building edges, or kerb intersections. These three pairs of corresponding non-collinear points were then used with the "Single Point Registration" tool to align each dataset to the backpack point cloud. The tool solves for a rigid-body transformation from the three-point constraints and applies it to the entire point cloud, removing the main translational and rotational offsets (Fig. 7).

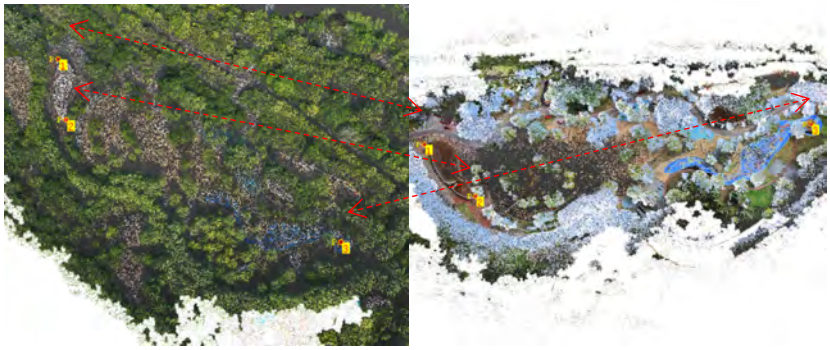

Fig. 7: Common control points selected across the three point clouds in RealWorks

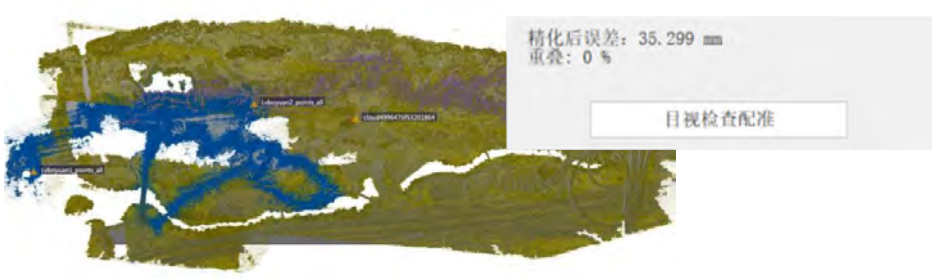

Fig. 8: Post-registration residuals after single-point (three-point) alignment

After three-point alignment, RealWorks generated a registration quality report, including average point-to-point distances and maximum deviations between datasets. In the China Green Expo case, the mean point-to-point distance between backpack and UAV LiDAR was about 35 mm, and the average deviation between the oblique and backpack point clouds was slightly larger but still at the centimetre level. Using the cross-section and local 3D visualisation functions, façades, road edges, and typical trunk locations were visually checked, and no obvious layer jumps, shearing, or ghosting were observed. After the three-point alignment, RealWorks automatically applied an internal ICP-based refinement without requiring manual setting of complex multi-scale parameters. Default settings were used, and the quality report

plus visual inspection were taken as evidence for registration reliability. Given GCP accuracy, instrument specifications, and the software statistics, we estimate that after registration the combined three-source point cloud has a park-wide RMS error of about 2-5 cm, which is acceptable and practically meaningful for most landscape planning and management tasks (Fig. 8).

3.3 Voxel-Based Weighted Fusion and Down-Sampling

After alignment, the three-point clouds were fused using a voxel-based weighted averaging approach. The study area was discretised into 0.1 m cubic voxels, each storing points from the backpack, UAV LiDAR, and oblique datasets. A height-stratified weighting scheme reflected the strengths of each source: backpack LiDAR was favoured for ground and trunk heights, UAV LiDAR for mid-upper canopy and roofs, and oblique data mainly for canopy outlines, façades, and texture. Within each voxel, coordinates were combined by weighted averaging, with colour preferentially taken from higher-quality oblique points.

To reduce noise and data volume, voxels supported only by sparse oblique points and strongly deviating from neighbouring LiDAR points were removed, and the fused cloud was uniformly thinned to a target density of roughly 200-300 points/m² in dense stands and 50-100 points/m² in open areas. This preserved the essential geometry of trunks, canopies, and building façades while greatly reducing file size and providing a coherent basis for subsequent analysis.

4 Comparison of Single-Source and Fused Point Clouds

When the three single-source point clouds are inspected and overlaid in the same representative test area, the differences and complementarities in their spatial information become clearly visible.

The backpack LiDAR primarily captures dense point clouds from a pedestrian perspective in understorey and near-ground zones. Viewed alone, trunk cross-sections, shrub volumes, pavements, and small landscape structures are clearly recognisable, and most points lie on physical surfaces with stable geometry. Among the three datasets, backpack LiDAR provides the best understorey detail and local accuracy. In areas with short viewing distances and limited occlusion, local accuracy can generally be controlled within 2-3 cm, and building façades and trunk profiles match field conditions closely. However, due to sensor height and path constraints, point density in canopy tops and roof areas is clearly insufficient, especially in stands of tall trees, leading to frequent patterns of “rich trunks and ground, but sparse canopy”. In addition, backpack surveys require an operator to walk the routes in the field; in this case, covering main roads and key areas took about 3 hours. Overall, backpack LiDAR is strong for detailed human-scale and understorey representation, but weak for upper canopy and large-area coverage (Fig. 9).

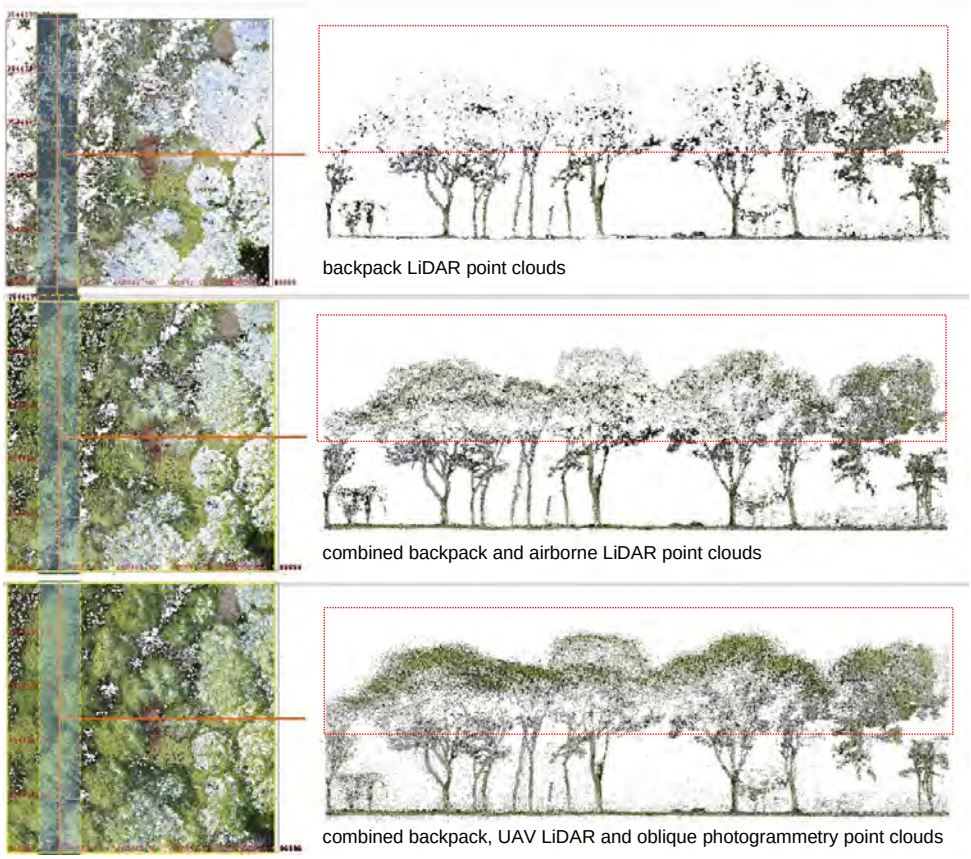

Fig. 9: Comparison of backpack LiDAR, UAV LiDAR, and oblique photogrammetric point clouds

UAV-borne LiDAR acquires data from an overhead perspective. Viewed alone, canopy and roof information is the most complete and continuous among the three, and at park scale it captures canopy cover patterns and elevation undulations effectively. Under repetitive scanning and multi-return settings, some canopy penetration is achieved and a certain number of ground and trunk points are collected, but under very dense canopies the understorey remains under-represented and trunk/shrub structures are still incomplete. Based on instrument specifications and GCP accuracy, the expected horizontal and vertical accuracy is about 4-5 cm under typical operating conditions. When overlaid with the backpack point cloud, offsets at building corners and kerb edges are generally only a few centimetres. Compared to oblique photogrammetry, UAV LiDAR offers more reliable geometry and height information, with stable ground and trunk positions. Compared to backpack LiDAR, it excels in coverage and survey efficiency: about 20 minutes of flight time were sufficient to cover the entire study area. UAV LiDAR, however, does not represent fine near-ground structures, low shrubs, and small human-scale facilities as well as the backpack data. In summary, UAV LiDAR is strong for efficient acquisition of large-scale canopy and roof structures, but weaker for understorey and detail (Fig. 10).

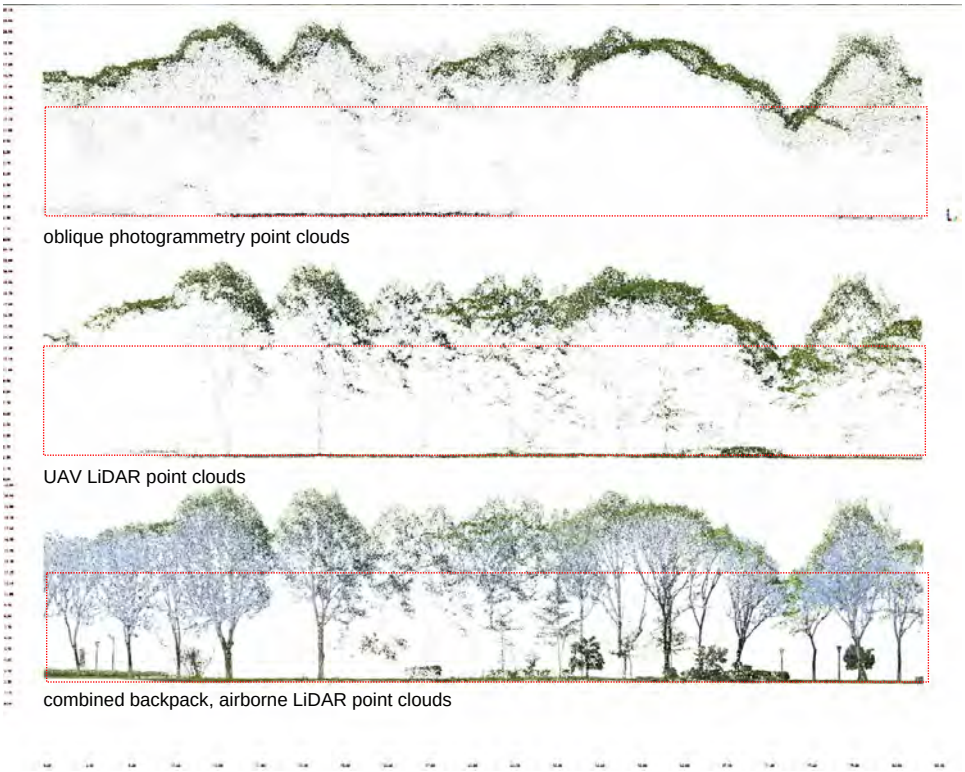

Fig. 10: Comparison of UAV LiDAR, backpack LiDAR, and oblique photogrammetric point clouds

The oblique photogrammetric point cloud is reconstructed from multi-angle imagery and shows relatively even spatial distribution. For the same area, it often contains more points than LiDAR, and among the three sources it provides the most continuous and intuitive outlines for tree crowns and building façades, while also carrying texture and colour information. This makes it well suited for visualisation and digital twin scenarios. However, its geometry is strongly influenced by texture, lighting, and viewing angles. Noise and floating points are common, and building corners or ground-façade junctions often appear blurred or not perfectly aligned with actual structures. Overall, geometric accuracy is lower than LiDAR, and there is no single official accuracy metric comparable to LiDAR specifications. It is therefore not suitable as the sole geometric basis for precise analysis. Its strengths lie in clear canopy skylines, rich textures, and relatively low acquisition costs (a small UAV with a high-resolution camera is sufficient), while its weaknesses are geometric reliability and limited understorey penetration (Fig. 11).

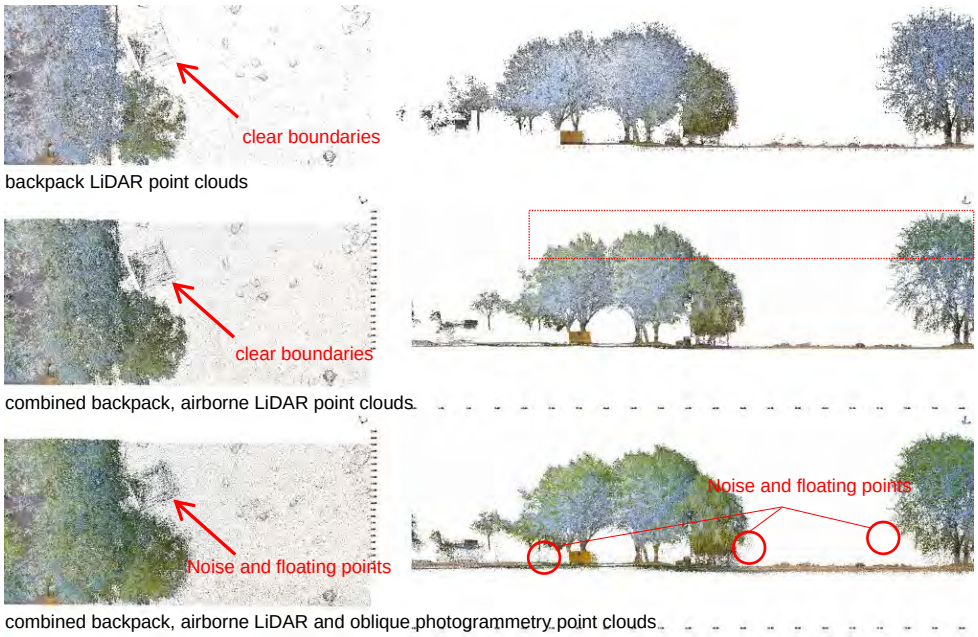

Fig. 11: Comparison of oblique photogrammetric point clouds with backpack and UAV LiDAR data

Considering geometric accuracy and information content together, after alignment and fusion the residual between backpack and UAV LiDAR in well-controlled areas is concentrated around 35 mm in building and road cross-sections. Combining multi-source errors and GCP accuracy, the overall RMS error of the fused point cloud is estimated at about 2-5 cm in both plan and height across the entire park. Height-distribution statistics for a representative area show that in single-source point clouds, point density varies strongly with height: backpack points concentrate at ground and trunk heights, UAV points at canopy and roofs, and oblique points around canopy outlines and façades. In contrast, the fused point cloud maintains relatively high and more balanced densities at ground, trunk, and canopy levels, which is advantageous for subsequent geometric analysis and visualisation.

From a fieldwork and processing perspective, backpack LiDAR requires on-site walking, leading to longer field time and the need for trajectory optimisation and adjustment during post-processing. This is best suited for high-detail surveys in priority areas. UAV LiDAR can cover large areas in multiple short flights, with relatively short processing times, and is the most efficient source in terms of coverage. Oblique photogrammetry has similar field time to UAV LiDAR, but dense reconstruction is more computationally demanding, and the resulting data volume is largest. Overall, UAV LiDAR is most efficient for wide-area coverage, backpack LiDAR is strongest for human-scale detail, and oblique photogrammetry is best for visual expression. Multi-source fusion inevitably adds processing and data management workload; whether to adopt it in practice depends on project accuracy requirements, budget constraints, and downstream applications. The strong complementarity among the three single-source datasets is the core motivation for constructing a multi-source fusion workflow.

5 Applications and Discussion

5.1 LAI Example Based on Fused Point Clouds

Leaf area index (LAI) is defined as the total one-sided leaf area per unit ground area and reflects canopy structure and light interception capacity. It is a key indicator for evaluating microclimate regulation and ecosystem services. A small-sample example illustrates the potential of multi-source fusion for more effective use of structural information, without attempting to establish a full LAI model in this paper.

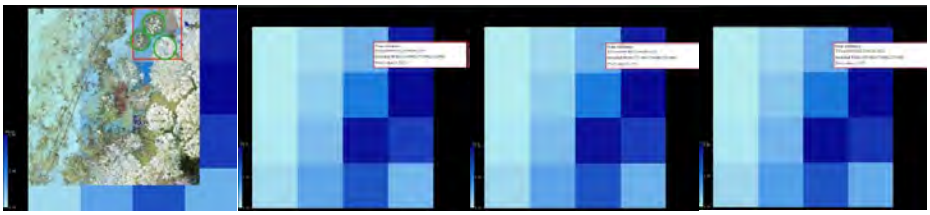

Fig. 12: Comparison of LAI estimates using backpack-only, backpack + UAV LiDAR, and full three-source fusion

The study area was subdivided into 5 m × 5 m grid cells, and for each cell the height distribution and point density of the fused point cloud were calculated. In one grid containing three Platanus × hispanica (London plane) trees, LAI was measured in the field using a LAI instrument, yielding three observations: 1.75, 1.86, and 2.05, with an average of about 1.886. LAI for this grid was then estimated using three configurations: backpack LiDAR only; backpack plus UAV LiDAR; and all three sources fused. The corresponding estimates were 1.217, 1.511, and 1.927. Backpack-only estimates are clearly too low, mainly due to missing canopy-top information. Adding UAV LiDAR significantly improves the estimate and brings it closer to the observed mean. The fused configuration provides the value closest to the average of the instrument readings (Figs. 12, 13).

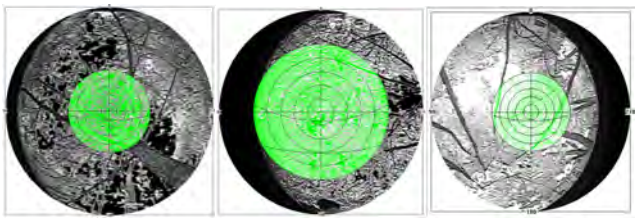

Fig. 13: LAI field measurement

Due to the very small sample size, this result can only be considered as an illustrative demonstration of the method's potential and does not replace a systematic ecological-indicator study. Nevertheless, the trend suggests that multi-source fusion allows more complete use of information at different height levels, enabling point-cloud-based LAI estimates to approach

field measurements more closely, and providing a basis for future systematic validation in larger sets of plots.

5.2 Single-Tree Segmentation and Structural Parameters

The fused point cloud also has potential advantages for single-tree segmentation and extraction of tree structural parameters. Based on the fused point cloud, a canopy height model can be generated at a chosen resolution, local maxima can be used to identify canopy tops, and a watershed algorithm can delineate canopy extents. In 3D space, Euclidean distance and height constraints can support region-growing to assign points to individual crowns. Tree height and crown width can then be derived: the backpack LiDAR provides trunk and lower-branch detail, UAV LiDAR supplements the upper canopy and outer crown surfaces, and oblique data add canopy outline and texture, which can in turn support manual or semi-automatic species identification (Fig. 14).

Fig. 14: Comparison of single-tree extraction from multi-source point clouds

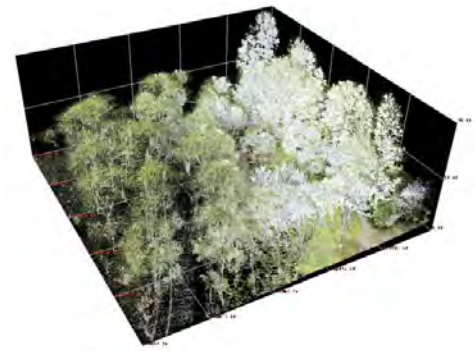

Fig. 15:
Example of clipped fused point cloud plot (50 × 50 m)

At present, this work has mainly been evaluated visually in several representative areas, and a comprehensive large-sample accuracy assessment has not yet been established, such as comparison to manually labelled trees with computation of precision, recall, or F1 scores.

This will be a focus of future research, in order to quantify how much multi-source fusion improves the accuracy of single-tree structural parameters.

Table 1 summarises recommended point cloud configurations and measurement paradigms for typical landscape tasks.

Table 1: Recommended point cloud configurations and measurement paradigms for typical landscape tasks

Application scenario	Main requirements	Recommended measurement paradigm (point cloud configuration)	Notes
Fine-scale design of small nodes (pocket parks, small features)	Detailed geometry of terrain, pavements, low vegetation, and structures; human-scale experience	Backpack LiDAR as primary source, optionally supplemented by limited oblique data	Backpack data capture human-scale and understorey space; oblique data enhance texture and visualisation
Understorey renovation in medium-sized parks	Understorey structure, continuous trunk-crown morphology, shading and view corridors	Backpack LiDAR + UAV LiDAR, with multi-source fusion	Combines understorey and canopy information; suitable for evaluating walking experience and understorey interventions
Large urban green space assessment	Canopy cover, vertical vegetation structure, large-scale terrain features	UAV LiDAR + nadir/oblique imagery, backpack LiDAR in priority areas	UAV LiDAR as main source for structural analysis; backpack data for detailed refinement at key sites
Public-facing digital twin visualisation	Realistic texture and colour, supported by adequate geometry	Oblique photogrammetry + UAV LiDAR, backpack LiDAR at key human-scale nodes	Oblique imagery provides visual realism; LiDAR provides geometric basis; backpack data strengthen human-scale realism at important nodes

Overall, multi-source fusion is not mandatory for every project. It becomes most "cost-effective" when high accuracy is required, when both understorey space and canopy structure need to be represented in detail, and when budgets permit the additional effort. The proposed workflow and comparative results provide quantitative references to support such decisions.

6 Conclusion

Using the China Green Expo Park in Nanjing as a case study, this paper develops and tests a multi-source point cloud fusion workflow for landscape analysis and management based on backpack LiDAR, UAV LiDAR, and oblique photogrammetry. The three datasets are clearly complementary: backpack LiDAR provides high-accuracy understorey and ground-level detail, UAV LiDAR efficiently captures canopy and roof structures at park scale, and oblique photogrammetry contributes canopy outlines and rich textures but with weaker geometric

reliability. All datasets were transformed into a common CGCS2000 Gauss-Krüger frame. We then applied height-stratified voxel-based weighted fusion with controlled down-sampling; the fused point cloud achieves higher spatial completeness, more consistent geometry, and a more balanced vertical information profile than any single source, while keeping data volumes manageable for subsequent analysis and visualisation.

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Decoding Landscape Spatial Structure with 3D Point Clouds and Complex Networks: Towards Parametric Rules for Park Design

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Abstract: Spatial structure forms the framework of landscape design, determining the organisation of landscape elements and playing a pivotal role in both designing and evaluating landscape spatial morphology. This study develops a multidimensional quantitative framework for analysing and visualizing the spatial structures of urban parks, integrating 3D point cloud data, ArcGIS, and Cytoscape-based network modelling. Thirty comprehensive urban parks were examined as case studies to identify the characteristic organization and spatial logic underlying different structural types. Six key indicators – structural extensibility, connection density, spatial transition frequency, network centralization, spatial fragmentation, and spatial diversity – were calculated to quantify spatial hierarchy, compactness, and heterogeneity. The analysis revealed that distinct organizational patterns, such as linear, looped, and hierarchical types, exhibit specific threshold ranges of these indicators, reflecting differentiated modes of spatial clustering and circulation logic. At the overall level, variations in network centralization and fragmentation correspond closely to different layout typologies (e. g., zonal, uniform, centralized). These findings demonstrate that the spatial organization of urban parks exhibits measurable regularities that bridge the gap between qualitative design concepts and quantitative spatial logic. The proposed framework not only enhances the precision of structural analysis but also establishes a data-driven foundation for evaluating, comparing, and optimizing landscape spatial configurations in future generative or parametric design applications.

Keywords: Urban green space, spatial morphological characteristics, spatial structure, network analysis, 3D point cloud

1 Introduction

Landscape spatial structure serves as the fundamental framework for spatial construction and represents the underlying artistic logic that ensures spatial integrity and systematic coherence (DEE 2004). As Feng (2010) points out, landscape experience emerges not from isolated spatial components but from the dynamic interactions among interconnected spaces. A well-organized spatial structure facilitates coherent functional arrangements and enhances visitors' perceptual and behavioural experiences (KAPLAN & KAPLAN 1989, MEDAKOVIĆ et al. 2024). However, the representation of design intent – typically through bubble diagrams and schematic structures – remains largely dependent on the designer's personal experience and subjective judgment (DO & GROSS 2001, YOON 2000). The spatial organization pattern, in essence, determines the overall configuration and visiting experience of a park, which can typically manifest as centripetal, looped, or sequential. However, this subjectivity often results in inconsistencies between the intended functional organization and the realized spatial relationships, leading to deviations in circulation patterns or overall spatial logic.

Previous studies have predominantly examined landscape spatial organization through qualitative interpretation and typological classification, such as centripetal layouts emphasizing

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focal spaces, looped systems organizing circulation continuity, and linear sequences structuring movement and visual progression (WANG 2018, YOON 2000), with limited emphasis on quantitative or scientifically rigorous analysis. The integration of digital technology, such as point cloud data and 3D modelling techniques, has significantly advanced the precision of landscape spatial analysis (URECH et al. 2020, WANG et al. 2020). Quantitative approaches including spatial syntax, geographic information systems (GIS), and spatial network analysis (SNA) have been increasingly applied to explore spatial relationships and accessibility (MA & CHENG 2020, WANG et al. 2022, ZHOU & HOU 2021). Nevertheless, research on the application of complex network theory to landscape spaces – particularly those where vegetation constitutes a key spatial structural element – remains insufficient.

From the perspective of spatial structure, this research addresses the following key questions: (a) How can the spatial structure of landscape environments be quantitatively modelled and visualized? (b) What are the distinctive structural characteristics of different organizational patterns in parks? To answer these questions, this paper proposes a 3D point-cloud-based method for structural element extraction, aiming to enhance the accuracy of spatial network model construction. On this basis, a quantitative description framework of both structural elements and overall spatial organization is developed, enriching the information contained in the spatial structural network and enabling a refined understanding of spatial logic. Furthermore, by analysing 30 representative park cases, the study identifies the characteristic thresholds of various organizational patterns, providing a data-driven foundation for design assistance and spatial optimization in future landscape design practices. This work bridges 3D perception-based spatial data with complex network logic to establish transferable, parametric rules for landscape spatial organization.

2 Methods

Rooted in the concept of spatial organization, landscape design aims to cohesively structure spatial sequences, employing spatial graphic language to modularize the overall landscapes through systematic structuring and deconstruction (WANG 2017). Landscape spaces are conceptualized as a nested series of units, arranged hierarchically from local to global scales. This study establishes a comprehensive framework for the quantitative analysis and visualization of landscape spatial structures by integrating multiple software platforms (including ArcGIS for spatial data processing and Cytoscape for network modelling) based on 3D point cloud data. The analytical procedure involves four main steps:

(1) Extracting spatial units from the 3D point cloud model. This study used ArcGIS to build a park 3D raster model from point cloud data, followed by slope analysis. Raster slope changes (i. e., edges of plant communities and buildings) were extracted as boundaries, discontinuous interfaces were manually completed by filling gaps < 5 m, gaps far smaller than the spatial unit scale, or inter-functional boundaries (WANG et al. 2020). Focusing on visitor-accessible spaces as spatial units, the study applied the minimum external modulus theory to screen units: those < 400 m² (20 × 20 m) were excluded or merged with adjacent units (YOSHINOBU 1985).

(2) Identifying spatial connections among these units. The connectivity between spaces is determined primarily by pedestrian accessibility, including direct spatial adjacency and road-

mediated linkage. Beyond referencing the 3D distribution of point cloud data, field verification was also conducted to eliminate errors arising from point cloud acquisition.

(3) Constructing complex structural networks. Spatial structure construction comprises two core components: network nodes (spatial units) and links (spatial associations). Using Cytoscape – an efficient tool for automated spatial network construction and analysis – the study built spatial structure networks based on the interrelationships of park spatial units, generating the overall network model.

(4) Calculating multi-dimensional indicators that describe spatial relationships, hierarchy, and connectivity. Spatial structure indicators (Table 1) are quantified with the help of ArcGIS and Cytoscape. Attribute statistics for the area, quantity, and serial path length of spatial units were performed using ArcGIS. Indicators marked with an asterisk (*) are derived from embedded algorithms after constructing the spatial structure in Cytoscape.

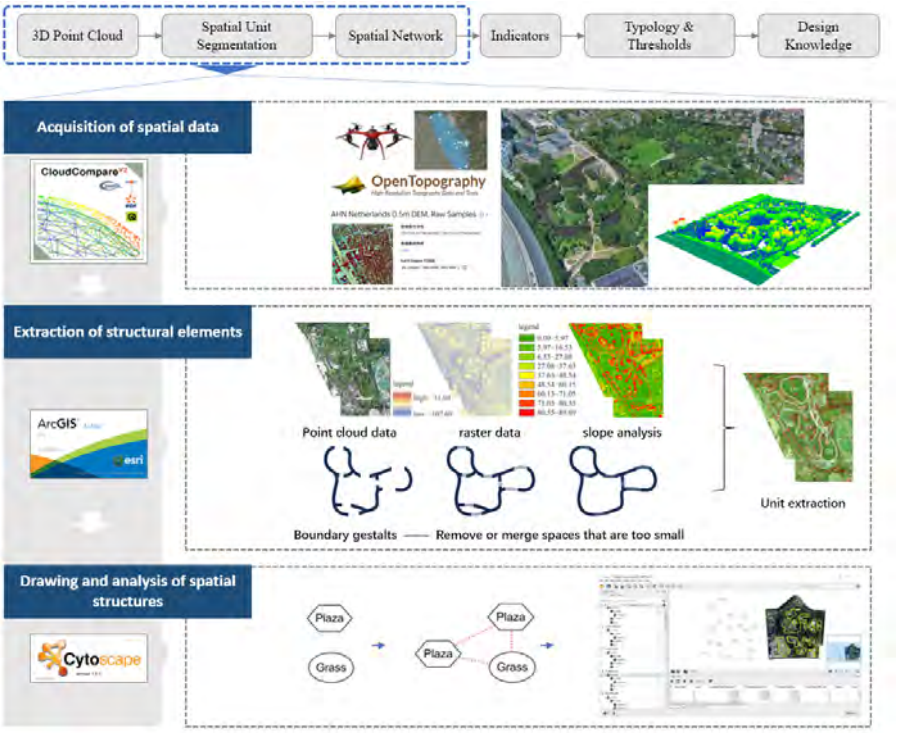


Fig. 1: Research framework: computational pipeline for landscape spatial structure extraction and analysis

Combining the theory of spatial organization and previous research, the study selects 6 key quantitative indicators and develops a multidimensional digital quantitative analysis index system to assess spatial structures. Some indicators of overall layout have been applied in previous studies (LU 2011, WANG et al. 2024), less attention has been given to group organ-

ization. This study employs indicators for group organization based on local network analysis (LIU 2004).

Table 1: Spatial structure indicators and calculation methods

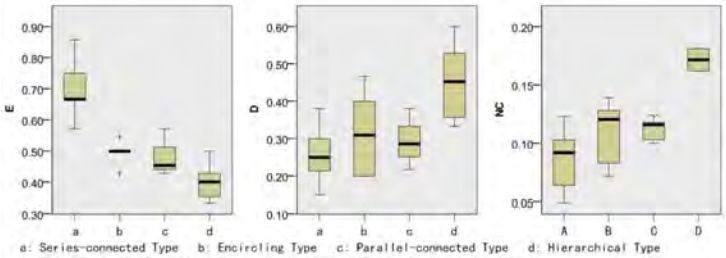
	Indicator	Explain	Calculation Formula
Compactness	Structural extensibility (E) *	Quantify the extension degree of the spatial group structure to characterize the diffusion range of the group.	$E = \frac{D_c}{N}$ D_c = structural diameter of space group c; N = number of space units in group c; E = structural extension of group c
	Connection density (D) *	Measure the connectivity degree among spatial units within the structure. A spatial structure reaches saturation when all units in the same group are fully connected, representing the tightest structural state.	$D = \frac{2M}{N\ (N-1)}$ M = number of associations between spatial units in the group structure; N = number of spatial units in the group; D = density of spatial connections in the group
Spatial transition	Frequency of spatial change (F)	Count the number of spatial unit transitions within a sequence of specific length to indicate the frequency of spatial change rhythms.	$F = \frac{N_r}{L_r}$ N_r = number of spatial units on the sequence r; L_r = length of the serial path of the serial sequence r; F = frequency of spatial change in sequence r
Layout aggregation	Network centralization (NC) *	Characterize the structural network's tendency to agglomerate around a specific node, which serves to assess the overall structural equilibrium degree.	$NC = \frac{\sum_{i=1}^{n}\ (C_{RDmax} - C_{RDi})}{n-2}$ and, $C_{RD} = \frac{C_{AD}}{n-1}$ C_{AD} = absolute centrality of each space unit; n = number of units in the space structure; C_{RD} = relative centrality of each space unit
Spatial heterogeneity	Spatial fragmentation (NF)	Assess the degree of spatial fragmentation. The fragmentation index shows an inverse correlation with the actual fragmentation degree of the spatial pattern; a higher index value indicates lower spatial fragmentation.	$NF = \frac{MPS\ (n-1)}{A}$ MPS = average size of spatial units; n = total number of spatial units; A = total area of spatial units; NF = spatial fragmentation
	Spatial diversity (ND)	Identify the number of spatial landscape types and the proportion of each type, which is employed to reflect the level of spatial diversity.	$ND = -\sum_{i=1}^{S} p_i \ln\ p_i$ S = total number of space units; p_i = number of certain spatial units as a proportion of the total number; ND = overall spatial diversity

Using 30 representative urban parks as empirical cases, the study systematically summarizes the quantitative patterns and threshold ranges of spatial structure indicators. These data are further categorized according to different spatial organization patterns, enabling comparative analysis of their structural characteristics. The derived threshold intervals not only serve as

reference criteria for landscape evaluation and design analysis, but also provide a data-driven foundation for generative design exploration and decision-making in spatial optimization.

3 Results and Discussion

Taking 30 comprehensive urban parks as case studies, this research adopted the analytical framework and indicator system to examine the spatial structure of parks. Fundamental spatial morphological data were measured to establish a database; based on the defined indicator formulas, quantitative analyses were conducted on the spatial organizational characteristics and community structures of each park. In SPSS, the community clusters were categorized into series-connected, encircling, parallel-connected, and hierarchical types according to the characteristics of each case, while the overall spatial patterns were divided into zoned, encircling, homogeneous, and centralized types. After assigning values (1,2,3,4) to the categorical variables of the cases, the Kruskal-Wallis (K-W) nonparametric test was performed. The results indicated that the factors E, D, and NC exhibited statistically significant differences across different types ($p < 0.05$) (Fig. 2). The box plots illustrate the distribution and variability of network indicators across different spatial organization types, highlighting their structural differentiation.



	E	D	F	NC	NF	ND
Chi-Square	23.476	12.272	9.956	17.192	2.993	0.493
Degrees of Freedom (df)	3	3	3	3	3	3
Significance	0.000	0.007	0.119	0.001	0.392	0.920

Fig. 2: Nonparametric factor test and multiple comparison analysis

Subsequently, the value ranges corresponding to different structural layout types were summarized via multiple comparison analysis and homogeneous subset partitioning (Table 2). The structural extension degree of the encircling and homogeneous types was defined as the union of their respective value intervals: [0.429, 0.571]. The connectivity density of the series-connected, encircling, and homogeneous types was determined as the union of their corresponding intervals: [0.150, 0.467]. The spatial agglomeration degree of the zoned, encircling, and homogeneous types was identified as the union of their trend intervals: [0.049, 0.139]. The remaining indicators showed no statistically significant differences and thus shared a unified threshold interval.

Table 2: Threshold ranges of spatial structure indicators

Category	Indicator	Threshold Range			
Group organi-zation	Pattern	Series-connected Type	Encircling Type	Parallel-connected Type	Hierarchical Type
	E	[0.571, 0.857]	[0.429, 0.571]		[0.333, 0.500]
		[0.333, 0.571]			
	D	[0.150,0.467]			[0.333,0.600]
		[0.15,0.60]			
	F	[0.0109,0.0262]			
Overall layout	Type	Zoned Type	Encircling Type	Homogeneous Type	Centralized Type
	NC	[0.049, 0.139]			[0.162,0.181]
		[0.049,0.181]			
	NF	[0.933,0.973]			
	ND	[0.523,0.999]			

Combining the quantitative results and typical cases (Fig. 3), it can be observed that the three indicators – E, D, and NC – are strongly correlated with spatial layout patterns. In particular, the Hierarchical Type is distinct from other types, characterized by relatively high spatial connectivity density and comparatively low extension degree of the clustered structure (WANG 2024). As illustrated by the cases in the figure, several spaces are intricately connected to form closely linked clusters, which can yield a rich path experience. By contrast, the Series-connected Type exhibits the highest extension degree; it typically consists of multiple spaces connected sequentially, emphasizing directionality and sequential experience. The Encircling Type and Parallel-connected Type fall between these two extremes.

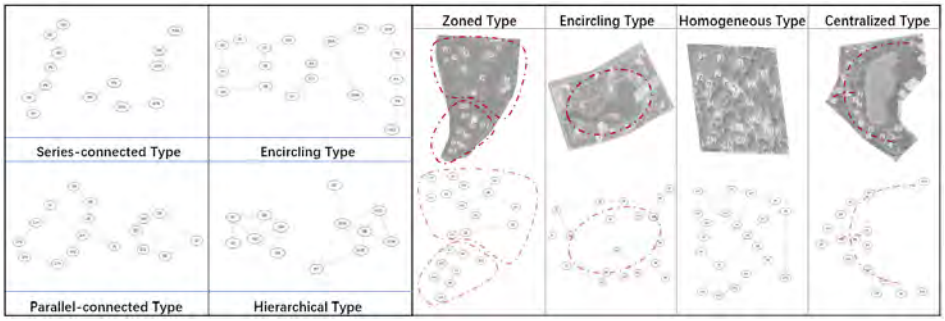


Fig. 3: Typical cases of park spatial structure

In terms of overall spatial patterns, the Centralized Type features the highest agglomeration degree, converging toward the central space to highlight its dominant status, with a clear hierarchical relationship within the space. By comparison, the importance of individual spaces is relatively balanced across the Zoned, Encircling, and Homogeneous Types (WANG 2018). In particular, the Encircling Type is largely constrained by site conditions, such as the

cases depicted in the figure where spaces form a ring around water surfaces. This correspondence provides an implicit validation of the computational framework through qualitative–quantitative alignment.

The quantitative method and indicators proposed in this study enable the quantitative characterization of the qualitative features of spatial structures. The summarized threshold ranges numerically assist designers in understanding and differentiating between spatial structures and layouts, thereby facilitating data-driven design generation and optimization. With the progressive advancement of artificial intelligence (AI) in the field of generative design, the controllability and interpretability of design outcomes have become crucial issues. The extracted structural indicators and threshold ranges can be directly encoded as constraints or evaluation criteria within generative design systems, enabling AI-assisted exploration of alternative spatial organization schemes (FAN et al. 2024). For the set of design schemes generated by AI, the indicator thresholds can serve as a basis for secondary scheme screening to help select spatial structures and layouts that meet design expectations; alternatively, they can be configured as one of the variables in multi-objective optimization to achieve quantitative control over the design process.

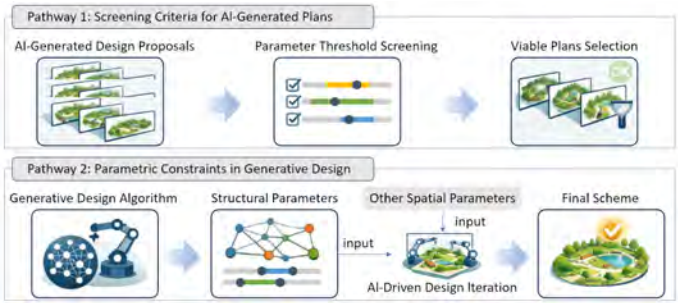


Fig. 4: Potential application pathways of the results in AI-aided design

4 Conclusion and Outlook

By constructing a 3D point-cloud-based structural network, this research quantitatively decodes the organizational logic of urban park spaces. The results confirm that spatial structure can be represented through quantifiable indicators with identifiable threshold ranges, reflecting both the morphological characteristics and functional coherence of landscape spaces. Linear and looped organizations tend to exhibit higher extensibility and moderate connectivity, while hierarchical structures show increased centralization and compactness. The identified thresholds and typologies reveal underlying spatial regularities that transcend subjective design interpretation. The consistency between computed structural patterns and widely recognized spatial characteristics of the case parks suggests that the proposed network-based indicators capture meaningful organizational differences rather than random numerical variation. Integrating complex network analysis with landscape spatial modelling provides a systematic approach to bridging qualitative design intent and quantitative evaluation. This study contributes a methodological basis for the objective assessment, pattern identification, and generative optimization of park spatial structures, offering theoretical and technical support for data-informed landscape design practice.

This framework has the potential to evolve into a scalable pipeline that links point-cloud-driven spatial perception, computational modelling of spatial logic, and AI-aided park design workflows. The proposed quantitative methods and identified spatial structural patterns offer a foundation for addressing existing gaps in spatial morphology research and may support designers in interpreting landscape spaces from an integrated, system-level perspective. In future AI-driven design processes, the extracted structural features and parameter threshold ranges could be incorporated as screening criteria for batch-generated design alternatives, assisting in the identification of spatially viable solutions. Furthermore, within intelligent design assistance systems, these thresholds may serve as constraint objectives, enabling parameter regulation within rational ranges and supporting more controlled and interpretable generative design outcomes.

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Empowering Trees: From Point Cloud to BIM – Realistic Reconstruction of Trees for the Effective Study of Their Impact in Urban Spaces

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Abstract: Realistic vegetation modelling remains a challenge within architectural and urban design, as evidenced by the widespread use of generic tree representations in BIM workflows. This work proposes to endow BIM tree objects with the specific values and characteristics that define them as unique individuals (empowering trees). A technical workflow is defined, which begins with the scanning of a tree using point cloud capture technologies, from which an informed 3D model is reconstructed and subsequently enriched with biophysical data. The resulting informed model enables more accurate simulations of the architectural and urban environment, providing relevant and reliable information for thermal and microclimatic analysis, as well as urban landscape planning.

Keywords: Realistic tree modelling, point cloud reconstruction, LiDAR-to-BIM, urban microclimate simulation, voxelization

1 Introduction

Contemporary architectural design faces the urgent need to mitigate the adverse effects of intensive urbanization. Particularly, the Urban Heat Island (UHI) phenomenon has been demonstrated to compromise thermal comfort and increase building energy consumption (SANTAMOURIS 2014). In this context, vegetation, beyond the capacity to improve the visual quality of urban spaces has emerged as a key and strategic environmental element, essential for regulating microclimates by reducing temperatures through evaporative cooling and shading on the ground (GRIMMOND & OKE 1999). Furthermore, numerous studies have consistently demonstrated that vegetation can directly reduce the energy consumption of buildings, providing significant savings both at the individual building scale (MCPHERSON et al. 1988, AKBARI 1997) and at the urban scale (DE LA FLOR 2004). Since the cooling capacity of vegetation is affected not only by spatial patterns, but also by morphological and physiological characteristics (LI et al. 2012), realistic representation of trees is crucial for conscious urban planning.

In the past two decades, real-world tree reconstruction has been the object of intense and fruitful investigation, yielding major advances in modelling structural geometry (high-fidelity LiDAR-derived), physiological function estimation (such as transpiration and precise biomass estimation), and temporal (4D) growth simulations. However, the lack of a unified methodology, as well as the integration of accurate tree geometries into the Building Information Modelling (BIM) workflow, remains a significant challenge (LUKA & GUO 2021, NIKOLOGIANNI et al. 2022, SHU et al. 2022). In BIM environments, trees are usually represented through geometric primitives (geometrical solids such as spheres, cylinders, ellipsoids and cones), efficient and suitable for rapid volume estimation and for generating photo-real-

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istic renderings (textures or billboards to simulate foliage). However, these techniques often prioritize visual appearance over morphological fidelity. This results in a limited representation of branching structures, canopy porosity, and species-specific traits. Consequently, the lack of biophysical attributes, such as Leaf Area Density (LAD), Leaf Area Index (LAI), and evapotranspiration, and insufficient geometric accuracy, significantly restricts the precision and reliability of urban microclimate analyses (XU et al. 2025). This deficiency affects the study of radiative transfer and cooling potential (RAHMAN et al. 2015), as well as the estimation of latent heat flux in energy studies and the quantification of ecosystem services such as carbon dynamics and pollutant removal (JANHÄLL 2015). The present work addresses this issue by proposing a guided automation workflow that begins with the generation of realistic 3D models of trees from point cloud scans for their subsequent integration into BIM platforms. Finally, the reconstructed tree model is compared with a generic tree model (e. g., a sphere or a cone) to quantify divergences in metrics and factors that affect urban environmental and microclimatic simulations.

2 Related Work in 3D Tree Reconstruction

The structural reconstruction of 3D trees from LiDAR data is generally addressed through two distinct specialized lenses: the geometric modelling of the skeletal structure (trunk and main branches) and the volumetric representation of the crown architecture (foliage and canopy). Depending on the objective and the techniques employed, these two components have been approached using various computational strategies in recent years. Regarding trunk reconstruction, classical fitting-based methods like Quantitative Structure Models (QSMs) have been widely used to adjust geometric primitives – typically cylinders – to point clouds and extract metric data (RAUMONEN et al. 2013). Recent advancements have proposed rigorous methods for surface reconstruction and tree-part segmentation to improve the fidelity of the trunk structure (TAKAHASHI & MASUDA 2021, HIRT et al. 2021). Furthermore, specialized segmentation strategies have been developed to enhance accuracy (WANG et al. 2016). Recent advancements have achieved high accuracy in geometric trunk modelling through advanced cylinder-fitting (KURDI et al. 2024a). While solutions like multi-scale curve fitting (WANG et al. 2023) effectively reduce metric error for forest inventory, skeletonization-based approaches (DU et al. 2019) offer superior topological connectivity. By exploiting intrinsic geometric properties, such as rotational symmetry, these methods are significantly more robust against partial occlusions and missing data typical of complex tree architectures.

On the other hand, crown reconstruction usually follows three main strategies: geometric shape approximation, computational geometry, or voxel-based methods. Geometric shape approximation models the tree crown as a 3D geometric solid, which often fails to adapt to irregular forms. Computational geometry approaches include: convex hull, defined as the smallest convex set containing a three-dimensional point set (BARBER et al. 1996); alpha shapes (EDELSBRUNNER et al. 1994), which are a generalization of the convex hull capable of capturing concavities depending on an optimizable alpha parameter (WANG et al. 2024); and wrapping surfaces which adapt more accurately to irregular crowns (KATO et al. 2009). Although these methods adapt well to irregular shapes, they struggle to detect internal voids (SUWARDHI et al. 2022, BURMEISTER et al. 2024). To address this, voxel-based methods divide the space into 3D pixels – voxels – (KAUFMAN et al. 1993), and have been widely applied to crown reconstruction (LECIGNE et al. 2017). Recent comparative analyses show that voxels

are more effective for evaluating the internal distribution of leaves and biomass (KURDI et al. 2024b).

In parallel, with the emergence of deep learning, neural networks have been proposed to address tasks related to reconstruction and semantic analysis of point clouds. These methods represent a significant contribution for solving partial reconstructions (BORNAND et al. 2024), particularly in cases of missing data or partial occlusion of tree elements, provided that relevant botanical patterns are properly learned by the model. However, they present limitations regarding point cloud size due to the high computational cost associated with training on large datasets exceeding one million points (LIU et al. 2021), and generally provide lower metric precision as they are fundamentally statistical in nature.

While existing literature provides robust methods for both skeletal and canopy reconstruction, these approaches often remains fragmented. A significant challenge persists in unifying these techniques into a cohesive, end-to-end workflow to enable the operational transition of high-fidelity models into Building Information Modeling (BIM), which is the primary objective of this study.

3 Methodology: The LiDAR-to-BIM Workflow

The proposed methodology is based on the classification of point cloud data into trunk and leaf points. A fitting-based strategy is adopted, combining both segmentation and skeletonization techniques for the trunk reconstruction while discarding deep learning due to the high computational cost of processing high-resolution Terrestrial Laser Scanner (TLS) datasets. For the canopy, the reconstruction follows the definition of the crown as the "sum of crown spaces filled with leaves" (ZHU et al. 2020), a concept that enables the extraction of more precise metrics. This starting point motivates the choice of voxelization to capture internal voids and canopy porosity, allowing the extraction of both qualitative metrics – geometric form and spatial distribution – and highly precise quantitative data. This approach is made feasible by the high-resolution nature of the input point cloud, which allows for small voxel sizes. This hybrid approach ensures a rigorous structural characterization, transforming the reconstructed geometry into an informed parametric model. A complete LiDAR-to-BIM workflow is proposed and defined in four sequential stages: (3.1) data acquisition and pre-processing, (3.2) point cloud processing, (3.3) geometric reconstruction (canopy voxel-based model and trunk skeletonization), (3.4) BIM integration and parametrization.

3.1 Data Acquisition and Pre-Processing

The acquisition of the tree geometry (Fig. 1) was carried out through terrestrial LiDAR scanning, obtaining a point cloud in LAS (LASer) format. The subject of this study is a *Platanus* × *hispanica* (London plane tree), one of the six specimens located in Plaça del Raspall (Barcelona, Spain) at approximately 41.401222° N, 2.160833° E (≈ 41°24'4.4"N, 2°9'39.0"E). The equipment utilized was a SHARE SLAM S20 handheld LiDAR 3D scanner, featuring 200,000 points/s, a 0.1-40 m range (10% reflectivity) / up to 70 m (80% reflectivity), 360° horizontal FOV with 59° vertical FOV (−7° to +52°), and RTK positioning (stated accuracy: 0.8 cm + 1 ppm horizontal, 1.5 cm + 1 ppm vertical). Aerial LiDAR was excluded due to the operational and regulatory constraints associated with drone flights in dense urban environments. Furthermore, the benefit of aerial scanning for this specific application was considered

redundant, as terrestrial scanning alone provides sufficiently dense and reliable measurements of both the trunk and the overall canopy architecture within an effective range of approximately 40 m.

After acquisition, the LAS point cloud is processed using CloudCompare to isolate the tree geometry by filtering out the surrounding urban context (buildings, streets, furniture, and ground). The cleaned dataset is then exported as a .txt file for integration into Processing (Java library), serving as the input for the subsequent reconstruction stages.

Fig. 1: Data acquisition: (a) real tree photography (b) scanned site location

3.2 Point Cloud Processing

The processing of the point cloud was implemented using the open-source Processing (Java-based) language to handle the high computational load required for large datasets (point cloud). The procedure consisted of the following steps (Fig. 2):

a) Data import and pre-processing: import of the .txt file into Processing, and application of noise filtering algorithms.
b) Spatial sectioning: partitioning the point cloud into equidistant horizontal Z-planes for the subsequent projection of nearby points.
c) Contour detection: detection of external contours of a group of coplanar points using a Convex Hull algorithm (JARVIS 1973), and generation of slice-wise enclosing curves (ring splines), consistent with contour-/slice-based strategies used in robust tree reconstruction from incomplete point clouds.
d) Point classification and segmentation: segmentation of the point cloud by classifying points as “trunk points” or “leaf points” depending on their relation to ring-like, generally cylindrical structures. The trunk is identified using a ROSA-based curve-skeleton extraction method (TAGLIASACCHI et al. 2009). This approach exploits point normal and a local rotational-symmetry prior to improve robustness to missing data in point

clouds. Consequently, this enables an initial classification of the lower trunk and main branches points, as circular patterns are clearly detectable due to the absence of leaves.

e) Skeleton extraction and refinement: definition of the trunk skeleton from the centroid of each ring through a recursive algorithm that traverses all points from bottom to top, classifying the main trunk and secondary branches (BUCKSCH 2014). Structural gaps caused by foliage occlusion or acquisition limitations are resolved through this method, which enables the connection of centroids across multiple planes when circular patterns are not detected in intermediate sections. Subsequently, a refinement step re-evaluates the point classification: leaf points located at a distance from the skeleton axis smaller than the average radius of the two nearest rings are reclassified as trunk points.

f) Multi-scale voxelization: voxelization of the points corresponding to the canopy at different scales (10, 15, and 20 cm) to allow for adjustable levels of definition. This approach facilitates varying Levels of Detail (LoD) in the final model, ranging from coarse volumes to high-resolution representations of the crown's internal structure.

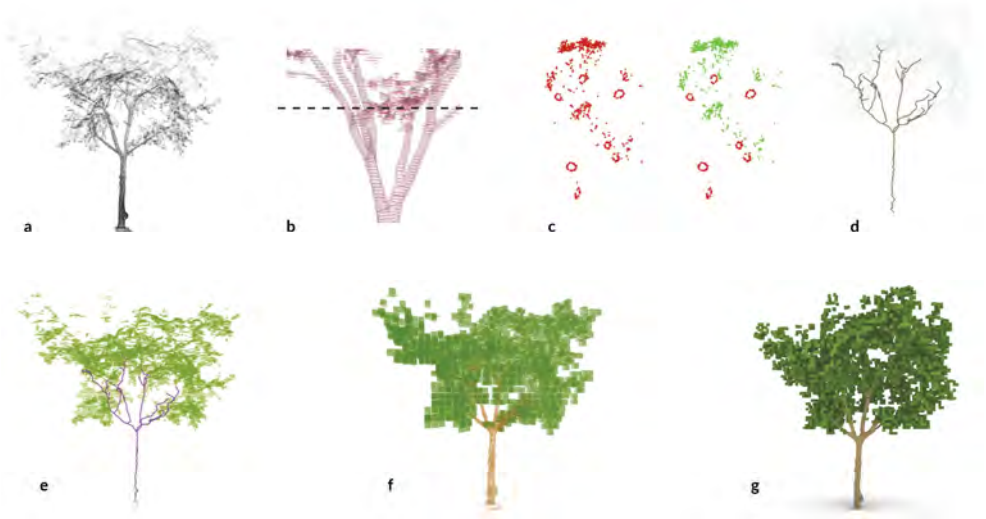

Fig. 2: Reconstruction process: (a) isolated tree from original point cloud; (b) sectioning; (c) leaf/trunk point cloud segmentation; (d) skeletonization; (e) skeleton and leaf points (f) crown voxelization; (g) final 3D model

3.3 CAD 3D Model Reconstruction

The trunk and secondary branches are automatically modelled using a Python script in Rhinoceros 3D, based on the rings and structural data imported from Processing, resulting in a continuous enclosing mesh. The leaf points are integrated into the tree model as voxels (short for “volume pixels”, the 3D equivalent of 2D pixels) representing spatial data as B-Rep solids. LiDAR scanner’s ability to capture individual leaves, or even continuous leaf surfaces, is inherently limited, both by the sensing system itself (resolution, incidence angles, and occlusions) and by external factors such as wind-induced motion. In practice, the scan mainly

provides evidence of where foliage is present (i. e., the spatial distribution of returns), rather than an explicit, leaf-by-leaf geometric reconstruction. Voxelization helps stabilize and extrapolate this information: by discretizing space into a regular volumetric grid, each voxel becomes a container that aggregates observations from the point cloud, such as occupancy (point count) or local density from segmentation. When combined with additional descriptors, such as leaf density parameters, this voxel-based representation enables the assignment of physically meaningful attributes to each cell (e. g., porosity, density gradients, vertical foliage distribution), even under sparse or incomplete sampling. Voxelization offers two key advantages. First, it naturally handles incompleteness and noise: missing leaves or sparse sampling does not break the model because the representation relies on local aggregated evidence rather than exact leaf geometry. Second, it enables multi-scale representations (LoD) by changing voxel size or adopting hierarchical grids, allowing the same dataset to support different tasks: coarse voxels for early-stage urban microclimate simulations (shadow casting, Sky View Factor approximations, volumetric blockage) and finer voxels for detailed canopy characterization.

3.4 BIM Integration and Parametrization

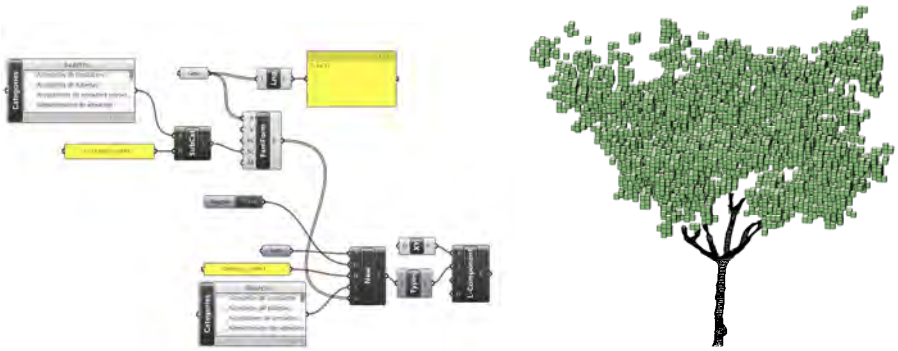

Fig. 3: Import process: script for transferring models from CAD to BIM environment

The 3D geometry generated in Rhinoceros 3D is integrated into the BIM authoring platform (Autodesk Revit) via Grasshopper and Rhino.Inside.Revit (RiR) (Fig. 3). This workflow overcomes the limitations of conventional geometry imports, which often restrict the parametrization of discrete objects. The canopy is transformed into a voxel list of native BIM elements. This step prepares the model for advanced data integration within the BIM platform. To support this, the tree model is mapped as an *IfcGeographicElement* (IFC 4×3), adopting a hierarchical structure where the trunk and foliage (voxel aggregate) are subordinate components of a single entity. This ensures the model recognizes these parts as belonging to the specific specimen. Once integrated, a Global Unique Identifier (GUID) links the geometry to its biophysical attributes, such as canopy density or carbon sequestration, stored within Property Sets (Psets). This approach enables direct calculations and automated scheduling, transforming the tree from a static graphic into a computational database for efficient information management.

4 Model Validation and Comparative Analysis

To validate the reconstruction fidelity, the 3D model was compared with physical measurements directly taken from the tree, such as the height to the first branching point and the trunk perimeter at various levels. Results showed a high correlation of 3D model with the tree, yielding an RMSE (Root Mean Square Error) of 4.24 cm, which confirms that the structural complexity captured by the point cloud is maintained throughout the reconstruction process. This metric validation provides the necessary reliability to quantify the discrepancies in environmental performance when compared to generic models.

To highlight the potential of utilizing realistic tree geometry in a BIM environment, a comparison is made between two simulation scenarios within a specific urban context (Fig. 4). The realistic scenario utilizes the high-definition model reconstructed directly from LiDAR scanning, represented by 6677 discrete voxels (0.10×0.10×0.10 m), which captures the natural porosity of the canopy. Conversely, the generic scenario employs a standard ellipsoid (principal axes of 8×6×8 m and a trunk height of 3.3 m) to approximate the overall dimensions of the specimen, as is common in conventional BIM workflows. The two scenarios are evaluated using geometric metrics and biophysical indicators that define the tree's environmental performance (Table 1): Shadow Projection (*SP*), representing the shaded area at ground level; Foliage Volume (*FV*), the volumetric measure that represents the portion of the canopy corresponding exclusively to foliar elements, excluding the trunk and the main structural branches; Geometric Accuracy (*GA*) defined as the ratio between canopy volume and projected shadow area ($GA = FV / SP$); Leaf Area Index (*LAI*), which quantifies the leaf surface density relative to the projected area ($LAI = FV \times \lambda / SP$), where the specific leaf density coefficient for this species for the London plane tree is $\lambda = 1.30$ m^2/m^3; and Carbon Sequestration (*CS*), representing the estimated annual carbon uptake ($CS = FV \times \rho$), where the volumetric biomass coefficient is $\rho = 3.15$ kg/m^3 for this species. To quantify the extent to which generic models overestimate the proposed indicators, the Percentage Difference was calculated using the realistic model as the baseline:

$$\Delta\% = (X_generic - X_realistic) / X_realistic \times 100.$$

Table 1: Geometrical and biophysical comparison between generic and realistic scenarios

	Geometrical Metrics			**Biophysical Indicators**	
Model Scenario	***SP* (m^2)**	***FV* (m^3)**	***GA* (m)**	***LAI***	***CS* (kg/yr)**
Generic Tree Model	54.54	200.96	3.68	4.79	633.02
Realistic Tree Model	38.18	6.68	0.17	0.22	21.04
Absolute Difference	16.36	194.28	3.51	4.57	611.98
Percentage Difference	**42.85%**	**2908.38%**	**2064.71%**	**2077.27%**	**2908.65%**

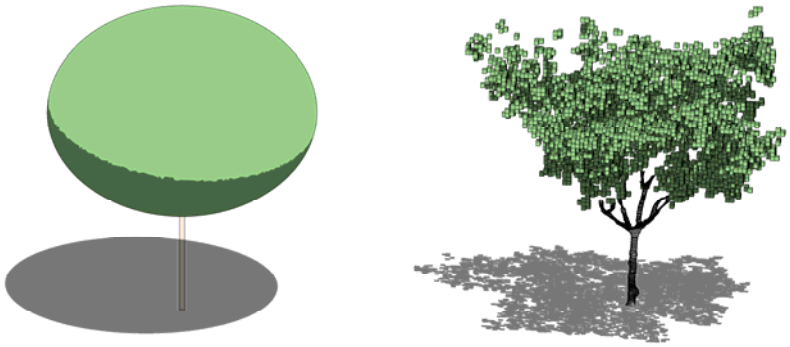

Fig. 4: Shadow Projection (*SP*): analysis of the generic and realistic tree model under the solar conditions of the summer solstice at 12:00 p.m. in Barcelona, Spain

5 Discussion

The comparison of generic and realistic tree model scenarios reveals critical discrepancies in geometric metrics and biophysical indicators. Shadow Projection (*SP*) provides the first crucial insight: the generic tree model overestimates the shaded area by approximately 43%. While the generic model incorrectly assumes 100% solar blockage within its boundary, the realistic tree model enables a more accurate calculation of solar transmittance and the resulting "dappled light" patterns, critical factors for urban microclimate analysis, thermal comfort, and cooling load calculations on both ground surfaces and building envelopes.

The most significant divergence is found in Foliage Volume (*FV*), where the generic tree model overestimates the volumetric occupation of foliage by 2908.38%. This massive inflation occurs because generic BIM objects are represented as solid geometric primitives, whereas the realistic model captures the true structure of the canopy, including the substantial empty spaces between leaves and branches. Consequently, the Leaf Area Index (*LAI*) shows a proportional disparity of 2077.27%. This morphological precision ensures that impact assessments are based on realistic biomass rather than simplified geometric abstractions.

This is further supported by the Geometric Accuracy (*GA*), which reveals a structural divergence of 2064.71%. This disparity highlights the fundamental inaccuracy of simplified representations. In terms of thermal comfort, utilizing the realistic *GA* ensures that wind speed reduction and evapotranspiration are modeled accurately, preventing the "wall effect" caused by solid geometric primitives and correctly reflecting the true porosity of the canopy.

Regarding Carbon Sequestration (*CS*), the implications are profound for air quality regulation, as it is directly proportional to active leaf surface area and biomass. The data reveals that relying on generic BIM volumes results in a massive CO_2 uptake overestimation of 2,908.65%. This discrepancy would lead to fundamentally flawed green carbon analyses and misguided environmental studies.

In conclusion, the consistent disparity across metrics proves that geometric primitives are inadequate. They fail to represent the complex structures necessary for reliable urban microclimate assessments. The proposed workflow effectively ‘empowers trees,’ transforming

their representation from placeholders into high-fidelity analytical entities capable of supporting rigorous urban environmental simulations. It makes their uniqueness and value more legible and, importantly, more quantifiable, both for urban decision-making and for recognizing the intrinsic value of trees.

6 Conclusion and Outlook

This research presents a pathway to overcome the limitations of generic vegetation in BIM through the rigorous use of LiDAR data. The integration of scanned tree models into BIM platforms supports the central thesis of this work: the need for accurate geometry within the tree model and analytical results to ensure the reliability of decision-making in architectural and landscape design. By treating the tree model as a data-rich entity where geometrical metrics and physiological data are intrinsically linked, this methodology moves beyond graphic representation. This approach allows the tree model to become an active component in the BIM environment, providing the rigor required for precise environmental simulations. The case study quantifies the divergence between a realistic and a generic tree model, proving that without morphological precision, simulations of solar control, cooling loads, and ecological services yield results that are fundamentally unreliable.

Future work should focus on scaling this approach by considering other specimens and verifying the impact of realistic morphology on urban-scale microclimate results. Additionally, the extraction of the tree model's branching topology opens a promising research line for forward growth simulation. By applying species-informed growth rules to the skeletonized network, it becomes possible to forecast future canopy expansion and porosity, enabling time-based projections of ecosystem services over the tree model’s simulated lifecycle.

Admittedly, the current methodology is time-consuming. It requires a level of computational expertise that currently exceeds conventional architectural workflows. Once the initial point cloud is manually segmented, the process achieves a high degree of automation, from skeletonization and voxelization to BIM integration. However, it currently functions as a guided automation, where automated data processing scripts require expert supervision to manage software transitions and parametrization. This complexity underscores the strategic need to develop specialized applications that streamline the transformation of raw point clouds into standardized, information-rich BIM objects. While technical restrictions like computational cost and file size remain, this work establishes a rigorous framework for providing the high-fidelity data essential for accurate environmental performance assessment.

Credit Author Statement

All authors contributed equally to the conceptualization, data curation, formal analysis, investigation, methodology, validation, and writing (review & editing) of the study.

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A High-Fidelity Microclimate Model Integrating 3D Point Clouds and OpenFOAM for Urban Heritage Tree Microhabitats

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Abstract: Urban heritage trees embedded in high-density cities are increasingly exposed to localized thermal stress due to surface hardening and restricted ventilation. Existing models, however, struggle to accurately resolve wind-thermal microclimate processes at this spatial scale. We propose high-fidelity microclimate modeling integrating 3D point clouds coupled with wind and thermal simulation software (OpenFOAM). By integrating realistic point cloud based environmental modeling with OpenFOAM, the method enables refined representation of heritage tree surroundings with complex vegetation and building enclosure. Validation against six hours of in situ measurements demonstrates that the proposed method reliably captures microscale thermal and airflow dynamics. The method enables quantitative identification of localized thermal risk and provides robust support for the conservation of urban heritage tree habitats and microclimate responsive site optimization.

Keywords: Urban microclimate, wind-thermal environment, heritage tree, 3D modeling, CFD simulation

1 Introduction

The combined effects of global climate change and rapid urbanization have intensified urban heat islands and ecological degradation (ZHONG et al. 2017). Vegetation systems play a crucial role in mitigating local climate issues and enhancing urban climate resilience through processes such as energy balance regulation, carbon cycling, and moisture exchange. However, in densely-built urban areas, surface hardening, building enclosure, and human disturbances deteriorate the microclimatic conditions in which vegetation exists, leading to significant fluctuations in local thermal and airflow conditions (LI et al. 2020). Particularly, urban heritage trees, with their declining physiological functions, are more vulnerable to climatic stresses and are often situated in highly impervious urban environments characterized by pronounced heat island effects (ESPERON-RODRIGUEZ et al. 2022). Therefore, their microclimate protection and habitat optimization require urgent attention.

Numerical simulation has emerged as a fundamental approach for quantifying environmental processes and predicting climatic responses, and it has been extensively applied in urban microclimate studies (BLOCKEN 2015). However, the spatial resolution of conventional microclimate simulations, typically ranging from a few to several hundred meters, is insufficient to resolve the fine-scale heterogeneity of urban heritage tree habitats. The limited geometric precision and coarse parameterization of these models constrain their capacity to resolve complex canopy structures and localized thermal variations, thereby reducing the accuracy of microclimate assessments (VURRO & CARLUCCI 2024). The open-source Computational Fluid Dynamics (CFD) platform OpenFOAM provides advanced multi-physics modeling capabilities and supports high-resolution simulations based on the Finite Volume Method

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(FVM). It enables precise computation of airflow, temperature, and turbulence fields within small-scale urban domains, allowing quantitative evaluation of how buildings, vegetation, and surface characteristics modulate wind and heat transfer processes (TOPARLAR et al. 2017). Previous studies have confirmed its effectiveness in representing typical urban scenarios such as street canyon airflow, park cooling effects, and terrain-atmosphere interactions (WONG et al. 2021, MUGHAL et al. 2021). Nevertheless, its application to structurally heterogeneous urban microhabitats remains challenging, particularly when dealing with interactions between vegetation canopies and surrounding buildings.

Understanding microscale wind-thermal processes around heritage trees is critical for guiding climate-responsive arboricultural interventions. To examine the wind-thermal characteristics of heritage tree microhabitats in urban built environments, we develop a high-fidelity microclimate simulation framework in OpenFOAM integrating dual-source point cloud data. The proposed framework combines unmanned aerial vehicle (UAV) based oblique photogrammetry with terrestrial laser scanning (TLS) to construct a high-resolution digital model of the real-world site. Subsequently, multi-physics boundary conditions, including wind velocity, air temperature, and turbulent heat transfer, are incorporated into OpenFOAM to simulate and validate the wind and thermal fields of the microhabitat.

2 Methodology

The methodological framework of this study is illustrated in Figure 1 and comprises three main stages: baseline data acquisition, model construction and numerical simulation, and model validation.

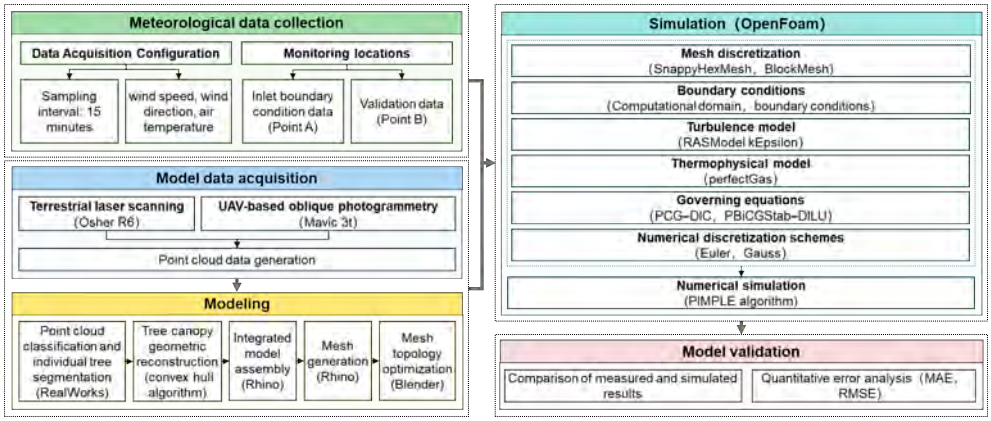

Fig. 1: Methodological framework of this study

2.1 Study Area

The case study focuses on the millennium-old *Juniperus chinensis* "Liuchaosong", located in the central urban area of Nanjing. As a remnant of the imperial garden landscape of the Southern Dynasties, this heritage tree is over 1,500 years old, with an approximate height of 12m, a diameter at breast height of 310cm, and a crown diameter of about 7m. Owing to

repeated damage from lightning strikes and windstorms, it has been officially classified as an endangered individual. The optimal growth temperature range for *Juniperus chinensis* is 15-30°C (https://news.huamu.com/). However, as a megacity in the Yangtze River basin, Nanjing has experienced sustained warming over the past five decades, with summer extremes reaching 41°C, exposing heritage trees to combined heat, drought, and urban heat island stress. "Liuchaosong" is situated within an approximately 1hm² enclosed built environment at the northwestern corner of the Sipailou Campus of Southeast University. The site is characterized by a relatively balanced composition of buildings, green spaces, and impervious surfaces, with gently undulating terrain and a vertically stratified vegetation structure. This spatial unit defines the microclimatic analysis domain adopted in this study (Figure 2).

Fig. 2: Study area and locations of meteorological monitoring points

2.2 Data Collection and Processing

2.2.1 Meteorological Data

To simulate typical summer conditions, two portable multiparameter meteorological stations (FT-SQ5) were deployed at monitoring points A and B within the study area on 24 June 2025 (Figure 2). Near surface wind speed, wind direction, and air temperature at a height of 2m were synchronously recorded from 12:00 to 18:00, with a sampling interval of 15 minutes. To represent extreme heat conditions, daily maximum air temperature data for the summer seasons from 2020 to 2024 were extracted from historical meteorological records (https://lishi.tianqi.com/). Based on these data, the extreme high-temperature scenario was defined as 311.15K. The reference wind speed was set to 0.6m/s, corresponding to the measured mean wind speed at a height of 2m within the site.

2.2.2 Site Modeling

High-resolution geometric modeling and optimization of the study site were conducted by integrating UAV-based oblique photogrammetry and terrestrial laser scanning point-cloud data, combined with parametric modeling and mesh-processing workflows. First, low-altitude oblique photogrammetry was performed using a DJI Mavic 3T UAV platform to acquire multi-view images of buildings, vegetation, and impervious surfaces, from which point-cloud data were generated. To enhance the level of detail in modeling individual tree crown structures, supplementary scans were carried out using an Ouster Intelligent R6 backpack-

mounted mobile LiDAR system. Point-cloud datasets from both sources were fused to produce a high-precision point cloud covering the study area (Figure 3). Subsequently, Trimble RealWorks software was employed for automated point-cloud classification and individual tree segmentation. Tree point clouds were extracted, and a convex hull algorithm was applied to preprocess the geometric envelope of each individual tree (LIN et al. 2017). Based on crown height and volumetric characteristics, 20 representative tree crown envelope types were constructed (Figure 4). In parallel, building and terrain information were extracted from the point-cloud data and reconstructed in three dimensions using Rhino software. Building heights ranged from 4 to 15m; for computational efficiency, architectural details such as windows, balconies, and other façade elements were omitted. After geometric refinement of all land-cover elements, the integrated model was converted into a triangular surface mesh and imported into Blender for topological optimization, including the removal of non-manifold edges, intersecting faces, and duplicate surfaces.

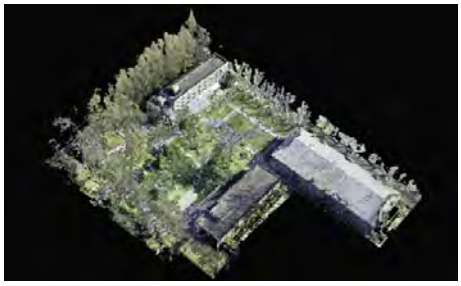

Fig. 3: 3D point cloud of the study site

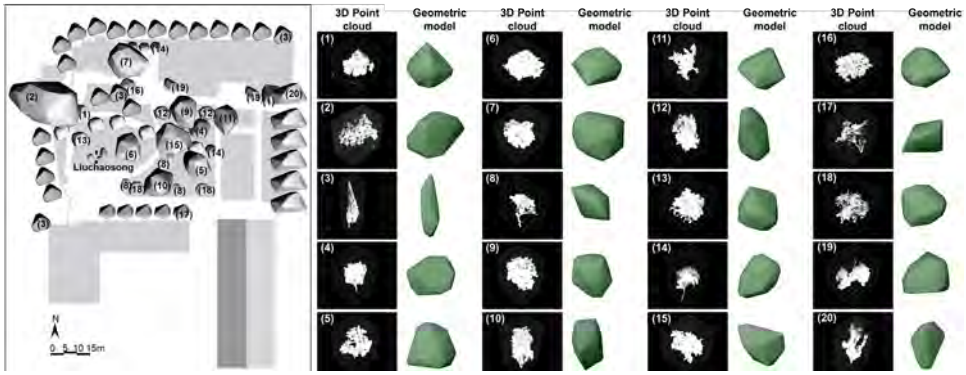

Fig. 4: Site model and geometric representations of 20 typical tree crown envelopes

2.3 Numerical Simulation and Model Validation

2.3.1 Mesh Generation and Boundary Condition Settings

3D mesh generation was performed using the snappyHexMesh utility in OpenFOAM. The final mesh comprised 1,493,320 cells, with a base resolution of 0.5m and local refinement to 0.25m in tree crowns and building regions (Figure 5). Mesh quality was verified using check-

Mesh and met the requirements for high resolution simulation. The dimensions of the computational domain were defined with reference to the methodology proposed by Jorg Franke et al. (FRANKE et al. 2011), resulting in a domain size of 400×400×60m. Taking the tallest object within the study area (30m) as the reference height H, the domain was extended approximately 5H in both the upwind and lateral directions, with an additional buffer of 1H above the domain to mitigate boundary effect. Boundary condition configurations are summarized in Figure 6. Under the typical summer condition, time-varying meteorological data measured in situ were imported using tableFile. Under the extreme heat condition, constant temperature and wind speed were set. To simplify computation and ensure initial thermal equilibrium, the initial temperatures of building facades, rooftops, and ground surfaces were uniformly set to 300K.

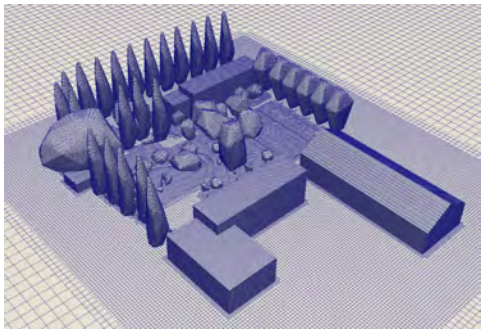

Fig. 5:
Computational mesh of the numerical model

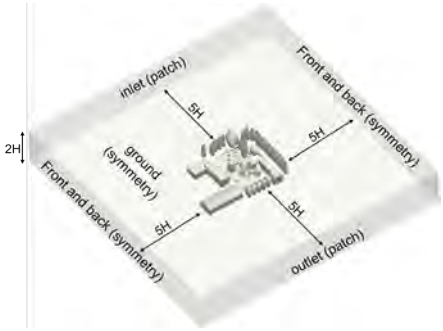

Fig. 6:
Computational domain and boundary condition configuration

2.3.2 Solver Configuration

Table 1: Solver configuration and numerical settings in OpenFOAM

Module	Setting	Module	Setting
Turbulence model	k – ε (RASModel: kEpsilon)	Numerical algorithm	PIMPLE algorithm (2 outer correctors, 3 inner correctors)
Thermo-physical model	perfectGas (C_p=1000 J/(kg·K), dynamic viscosity $\mu = 1.8 \times 10^{-5}$ kg/(m·s), Prandtl number Pr=0.7)	Spatial discretization	Convection term: Gauss upwind; Gradient term: linear corrected; Laplacian term: corrected
Energy equation	sensibleEnthalpy	Pressure equation	PCG-DIC
Temporal discretization	Euler	Velocity and enthalpy equations	PBiCGStab-DILU

The buoyantPimpleFoam solver in OpenFOAM v9 was employed to simulate the coupled wind and thermal environment surrounding the heritage tree. This solver is designed for transient simulations of compressible flow and explicitly accounts for buoyancy effects and sensible heat transfer, making it well suited for resolving thermo-momentum coupling processes

in small-scale outdoor environments. The detailed solver settings are provided in Table 1. For the typical summer condition, the model was first run to a stable state at 12:00 and the resulting solution was used as the initial condition for a six-hour transient simulation from 12:00 to 18:00, capturing the microclimate evolution under pronounced thermal responses. For the extreme heat condition, simulations were continued until both the flow field and temperature field reached a quasi-steady state, enabling the assessment of thermal environment distributions under stable but adverse boundary conditions.

2.3.3 Model Validation

Model validation was conducted using in situ measurements collected at monitoring point B within the study area as a reference. To quantitatively assess the agreement between simulated and observed values, two error metrics were employed: the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE).

3 Discussion

3.1 Consistency Validation

Consistency validation was conducted by comparing 25 sets of measured and simulated temperature and wind speed data collected at monitoring point B during the period from 12:00 to 18:00 (Figure 7). The results indicate that the model exhibits good applicability and reliability. Simulated air temperature shows a high level of agreement with observations, with an RMSE of 0.782K and an MAE of 0.654K, corresponding to approximately 0.2% of the background temperature. Simulated wind speed is slightly underestimated overall; however, its temporal variation trend remains consistent with the measurements, yielding an RMSE of 0.207m/s and an MAE of 0.188m/s. Overall, the model is capable of accurately capturing the coupled wind-thermal characteristics of the microclimate surrounding the heritage tree.

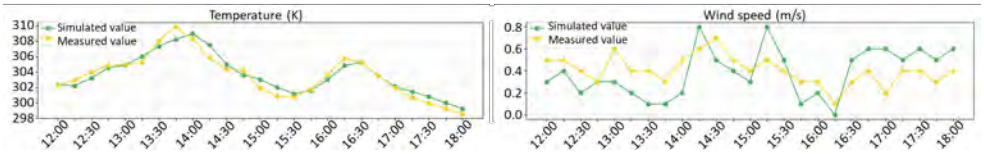

Fig. 7: Validation of simulated and measured temperature and wind speed at monitoring point B

3.2 Similarities and Differences in Wind-Thermal Spatial Patterns under Typical and Extreme Conditions

Microclimate simulations were conducted for Liuchaosong under typical summer and extreme heat conditions. Horizontal patterns of temperature and wind speed were generally consistent, but differences appeared in thermal stress duration and vertical wind speed distribution (Figure 8-10).

In terms of similarities, vegetated areas in the northwestern corner and the central part of the site maintain relatively low-temperature characteristics under both scenarios, whereas open

areas in the eastern and southwestern portions consistently function as high-temperature zones. Previous studies have demonstrated that green spaces can significantly reduce local air temperatures during daytime high-temperature periods through evapotranspiration and shading effects, particularly in areas with intact tree canopies and higher spatial enclosure (YU et al. 2024, NEVERS et al. 2025). With respect to wind speed, both scenarios exhibit an increase in wind speed with height, and areas below 10m are generally characterized by low wind velocities. Transitional zones of wind speed formed along the edges of buildings and vegetation show a high degree of spatial overlap between the two scenarios.

In terms of differences, under the typical summer condition, Liuchaosong experiences temperatures outside its optimal growth range for approximately half of the simulated period. Areas lacking vegetation cover and building shading consistently function as high-temperature zones, whereas shaded areas maintain relatively lower temperatures, although the temperature contrast between hot and cool zones is modest during certain periods. Under the extreme heat condition, overall temperature levels exceed the suitable range for Liuchaosong across the entire site, and spatial temperature disparities are further amplified. This suggests that under severe thermal stress, shading and evapotranspiration continue to provide mitigating effects but are insufficient to offset the substantial elevation of the background temperature. Differences are also observed in wind speed distribution. Under the typical summer condition, the location of Liuchaosong generally remains within a low wind speed zone; however, as airflow intensifies in the late afternoon, a relatively distinct east-west ventilation corridor emerges locally, whereas north-south corridors remain weak. In contrast, under the extreme heat condition, overall wind speeds are more constrained, and no effective ventilation corridors develop in the vicinity of Liuchaosong, resulting in prolonged exposure to low wind speed conditions.

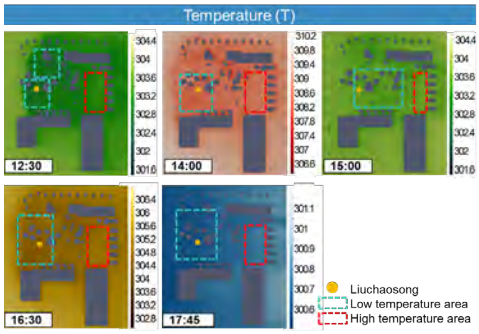

Fig. 8:
Spatial distribution of air temperature under the typical summer condition

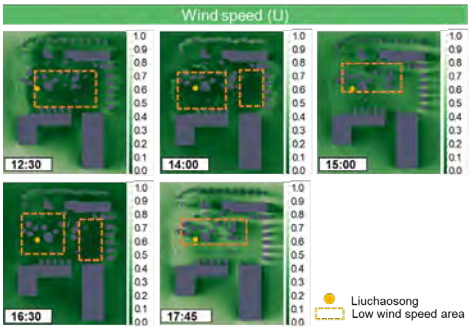

Fig. 9:
Spatial distribution of wind speed under the typical summer condition

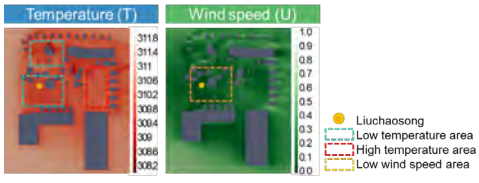

Fig. 10:
Spatial distributions of air temperature and wind speed under the extreme heat condition

3.3 Synergistic Effects of Wind and Heat

The spatial coupling between wind and thermal conditions is a key mechanism governing the formation of urban microclimate systems (ZHU et al. 2023). In this study, five points were randomly selected within low-temperature zones and high-temperature zones, respectively, to construct joint variation plots of temperature and wind speed (Figure 11-12). The results indicate that low-temperature zones are often associated with environments characterized by relatively high vegetation coverage and low wind speeds. In both high- and low-temperature zones, temperature peaks frequently occur during periods of low wind speed, while temperature rise phases are typically accompanied by relatively stable conditions with limited airflow. Insufficient wind speed may lead to localized radiative and thermal accumulation, thereby reducing air exchange efficiency. These patterns highlight the regulatory role of wind speed in heat dissipation. In open areas, higher wind speeds enhance convective heat transfer, allowing accumulated heat to disperse more rapidly; despite higher surface temperatures, localized heat retention remains limited. Conversely, in enclosed or semi-enclosed spaces, low wind speeds restrict heat dissipation. Even when surface temperatures are relatively low, heat and moisture may accumulate, resulting in thermally uncomfortable conditions.

Furthermore, wind speed transition zones and temperature gradient zones exhibit strong spatial coupling. In particular, the boundaries between buildings and tree canopies function both as zones of abrupt wind speed variation and as areas with pronounced temperature gradients. This phenomenon indicates that the effects of spatial structure on wind-thermal coupling are inherently nonlinear. Microclimate regulation therefore does not depend on the optimization of a single factor, but rather on the coordinated configuration of multiple elements including heat sources, vegetation, shading, moisture, and airflow.

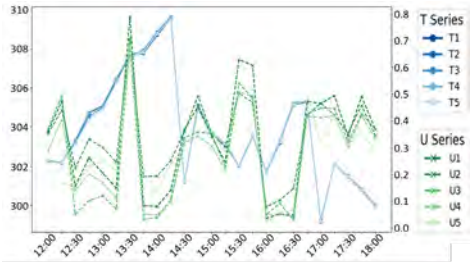

Fig. 11:
Coupled variation of temperature and wind speed in high-temperature zones

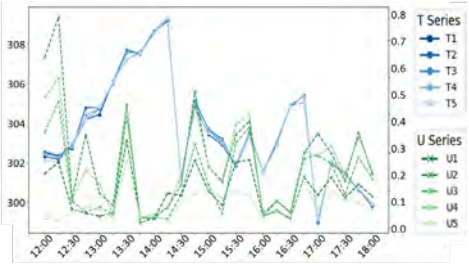

Fig. 12:
Coupled variation of temperature and wind speed in low-temperature zones

4 Conclusion and Outlook

This study developed a high-resolution 3D environmental model based on point cloud data and integrated it with OpenFOAM-based numerical simulations to propose a refined microclimate simulation approach for the microhabitats of heritage trees in high-density urban environments. The results indicate that the spatial patterns of air temperature and wind speed around heritage trees are primarily governed by spatial configuration and underlying surface

characteristics, and remain highly stable under both typical summer and extreme heat conditions. This stability indicates that optimization strategies based on spatial structure have long term regulatory potential. Further analysis reveals a pronounced synergistic interaction between wind speed and the thermal environment. Insufficient wind speeds tend to exacerbate heat and moisture accumulation, whereas excessively high wind speeds may adversely affect tree stability and water balance. The proposed methodology provides a practical diagnostic framework for identifying microclimatic stress factors that influence the health of urban heritage trees and supports informed decision making for their long term conservation and site specific management. Future research may incorporate solar radiation transfer and dynamic humidity processes to establish a more comprehensive microclimate simulation framework, thereby providing technical support for climate-responsive optimization of urban microhabitats and for the refined, adaptive management of long-lived ecological assets such as heritage trees in high-density cities.

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Design of Complex Naturalistic Planting in a Landscape Information Model

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Abstract: A computational workflow for designing complex, naturalistic plantings is implemented within a Landscape Information Model (LIM). Combining traditional design strategies, site processes and digital methods, this approach enables species-specific placement rules, visualisation and documentation at an individual plant level. This may lead to improved design precision, iteration efficiency, and integration with site implementation processes.

Keywords: Planting design, digital landscape architecture, Landscape Information Model, computational design

1 Introduction

There is increasing recognition of the benefits of plantings in public spaces that are both high in species richness and spatial complexity (ALIZADEH & HITCHMOUGH 2020). Success of these complex plantings is dependent on design, implementation and management processes which have been developed in the context of more traditional planting approaches with a smaller species palette and less complex distribution patterns (HANSEN & STAHL 1993, RAINER & WEST 2016). The increasing popularity of naturalistic planting design approaches is evidenced by both appearances in public projects, and an increase in use of the term, as shown in Figure 1 in publications from 1990-2022. This N-gram data shows the decline in references to 'formal planting' and an increase in references to 'naturalistic planting' and 'native planting' during this period. The major spike in interest in 2004-2009 may correspond with the opening and publication of several prominent public naturalistic planting projects such as the Lurie Garden and High Line.

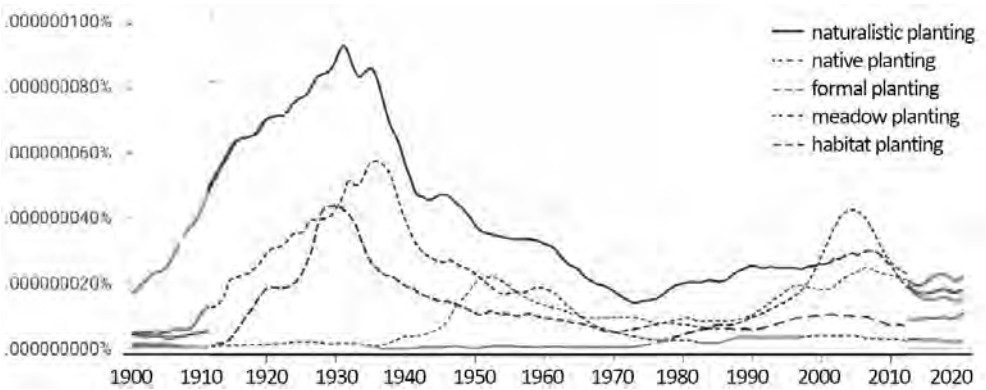

Fig. 1: Popularity of planting design terms 2000-2022 (GOOGLE 2025)

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The methods of planting design documentation and the design language of random matrices, 'drifts' or 'clusters' of same-species groupings and formal linear or geometric arrangements are familiar concepts in planting design and landscape architecture (DUNNETT et al. 2004, ROBINSON 2016). Planting design and documentation methods may be described as a gradient from fully randomly located to each plant nominated to a specific location (KIRCHER et al. 2012). Each of these methods has an impact on the success and visual impact of the planting, as well as the labour of initial design, drawing revisions, substitutions and time spent on site. The shift towards digital practice and design methods has in some cases de-emphasised natural systems and planting design compared to hard structural elements, and further development of planting design tools is needed in Landscape Information Models (LIM) to help address this gap (WHITE et al. 2020, ZAJICKOVA & ACHTEN 2013). This paper examines a method for the use of computational design principles in the design and documentation of complex naturalistic plantings in a LIM.

1.1 Computational Approaches to Planting Design

Table 1: Existing computational tools for planting layout in landscape architecture

Type	Examples	Platforms
Design Software	Land F/X / Planting F/X, Lands Design / Vectorworks Landmark	AutoCAD / Revit/Rhino / Grasshopper / Vectorworks
	LandKit	Rhino / Grasshopper
Render Software	V-Ray Scatter, Lumion, Twinmotion, Unreal Engine, Enscape	Rhino/SketchUp/Revit, Revit, Rhino, SketchUp, Archicad, Vectorworks, Standalone
Research Applications	Arevalo Alvear (2020) – 'Algorithmic Plant Communities'	Rhino / Grasshopper
	Belesky – GroundHog Plants tools	Rhino / Grasshopper
	Bilurbina, Abellan & Christodoulou (2019) – Cellular Automata planting patterns	GIS / CAD

Planting tools in industry-standard CAD/BIM platforms including AutoCAD, Revit, Vectorworks, and Archicad, remain relatively limited, reflecting the priorities of the larger architecture and engineering sectors over the comparatively smaller landscape design market (FRITSCH et al. 2019). This gap has been filled largely by specialist vendors who distribute planting capability as add-ons or plugins to these mainstream design and documentation environments. As summarised above in Table 1, existing approaches to planting design in digital landscape architecture can be described as belonging to one of three categories: production-oriented commercial design and documentation software, rendering and visualisation software, and more complex approaches inspired by ecological realism described in research literature. Documentation tools typically allow the arrangement of plant-objects into arrays and repeated patterns, foregrounding documentation, tagging, and scheduling, sometimes extending into automated functions such as area fills or modular tools (e. g. Land F/X / Planting F/X, Lands Design, and Vectorworks Landmark). Parallel to these are constraint/rule-based parametric planting workflows, such as LandKit or GroundHog which distribute plants using a plant database and environmental constraints governed by user-defined rules (BELESKY 2024, LANDAU 2025). In commercial rendering software, a complex or realistic planting dis-

tribution can be achieved through high-efficiency instancing/scatter pipelines that generate points on surfaces, edges, and splines, sometimes with semi-automated inputs such as "paint" placement, line placement, cluster placement, and species mixes (e. g., V-Ray Scatter, Lumion, Twinmotion, Unreal Engine, Enscape). A number of non-commercial research prototypes have explored alternative approaches including agent-based/parametric methods for populating planting areas and procedurally assigning species and spacing (AREVALO 2019, WHITE et al. 2020), cellular automata models that form discrete, grid-based planting patterns via neighbourhood and stochastic update rules (BILURBINA et al. 2019), and procedural frameworks for plant geometry generation plus rendering/illustration styles and scene assembly (DEUSSEN 2003, M'CLOSKEY & VANDERSYS 2017). Additionally, several emerging AI-driven methods for both plant species selection and distribution have been developed (LANDAU 2025, LIU et al. 2024).

2 Methods

2.1 Overview

In this paper we propose a methodology which draws from traditional planting design concepts such as matrices, drifts, clusters and modules and applies them to a systematic computational design methodology, following a rule-based procedural setout process equivalent to processes that take place on site. Individual plants are set out in layers from a dynamic schedule input, allowing designers to review and iterate before proceeding. This system is implemented in Autodesk Revit software, with the procedural logic in Python. It uses lightweight planting family instances to document planting designs in Revit. Planting areas are drawn that describe the extent of planting mixes. Each planting mix is a collection of species, ratios and distribution rules that is identified by a unique code in the Name parameter. Many previous computational methods for planting layout rely on parametric processes that are inspired by ecological processes or patterns in natural vegetation communities, but may not be practical to implement on site. The method uses a sequential best-candidate (farthest-point) stochastic placement algorithm with cluster-based offspring sampling, with the following steps:

1) Compute targets: For the selected planting mix, compute the required number of individuals per species from the mix definition and plan to realise each species as one or more clusters until its total is met.
2) Select a cluster centre (dispersed seeding): For each new cluster, sample multiple candidate centres uniformly within the area boundary at random, computing each candidate's distance to the nearest already-placed plant, and choose the candidate that maximises this nearest-neighbour distance (a best-of-random, farthest-point heuristic).
3) Instantiate the cluster: Around the chosen centre, sample the required number of plant locations uniformly over area within a circular neighbourhood whose radius is scaled by the species spacing and a user-defined spread factor; reject and resample any points outside the admissible interior, using a conservative fallback if repeated rejection occurs.
4) Repeat until complete: Repeat Steps 3-4, decrementing the remaining plant counts each time, until all species totals are satisfied, and moving on to remaining species.

2.2 Input Schedule and Rules

Input from planting designers is managed through a shared data table identifying plant species, density, spacing and distribution strategy for each mix. These provide the instructions for the detailed planting plans to be produced computationally including individual plants, leaders and symbols.

Table 2: Input parameter schedule for an example planting mix specification

Key	Species	Layout	per 10m2	Cluster	Symbol	Spacing (mm)
DG-A	*Andropogon 'Blaze'*	*Drift*	3	1	▲	300
DG-A	*Anigozanthos 'Landscape Lilac'*	*Cluster*	1	1	·	200
DG-A	*Arthropodium strictum*	*Swathe*	10	5	·	150
DG-A	*Austrostipa elegantissima*	*Matrix*	10	1	⊗	200
DG-A	*Austrostipa rudis*	*Matrix*	5	1	·	200
DG-A	*Bulbine bulbosa*	*Matrix*	10	1	·	200
DG-A	*Bulbinella nutans*	*Matrix*	7	1	·	200
DG-A	*Carex testacea*	*Matrix*	5	1	·	200
DG-A	*Cymbopogon refractus*	*Matrix*	3	1	·	200
DG-A	*Dicantheum sericeum*	*Matrix*	10	1	·	200
DG-A	*Drimia maritima*	*Matrix*	3	1	◍	200

2.3 Visual Output and Iteration

With individual plant-objects created in the LIM, species can be visualised either as simplified 3D representations, linked to render-assets or represented symbolically in planting plans and diagrams.

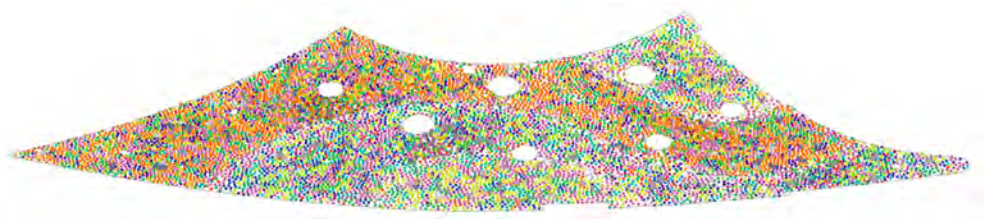

Fig. 2: Visualisation of planting scheme for design feedback and iteration

The computational strategy for distribution was developed through discussions with designers and horticultural staff to be both pre-computable and representative of a process that will be followed on site. This has the advantage of being both closely linked to the expected final outcome, and useful in making discoveries about the process of conception to reality. Instruc-

tions to the site team are a 'human-language' description of the same process, in which plants are placed following an ordered list, with new individuals or clusters placed in the visually identified largest gap in the current area, and clusters or drifts placed at a nominated offset adjacent to the first. An algorithm was also developed to visualise this on-site process of setting out plantings on site using the methodology described above by worker-agents, to provide clarity to contractors and the site team of how to achieve a complex planting layout. The ability to demonstrate and review the set-out process step-by-step assisted in providing a shared understanding and confidence in the delivery of a complex scheme.

3 Results

A test case on a real project was conducted with 41 unique naturalistic planting mixes and over 250,000 individual plant instances generated using the described method. 381 unique plant species were included and represented as family types within the LIM with parameters for botanical names, pot sizes, location within the project model and a 3D location. Time required for initial layout generation and updates is correlated with the area of planting and number of instances, with a layout of 15,000 plants taking approximately 120 seconds for generation. Due to the situation of the tool within a LIM platform this process also includes the production of schedules for total plants in the project and per-area summaries. Design revisions and iterations to planting mix layout, species substitutions, composition and setout rules can be made by editing the input schedules within Revit and re-generated with a similar time cost. Data for the time required to produce detailed documentation manually of this type

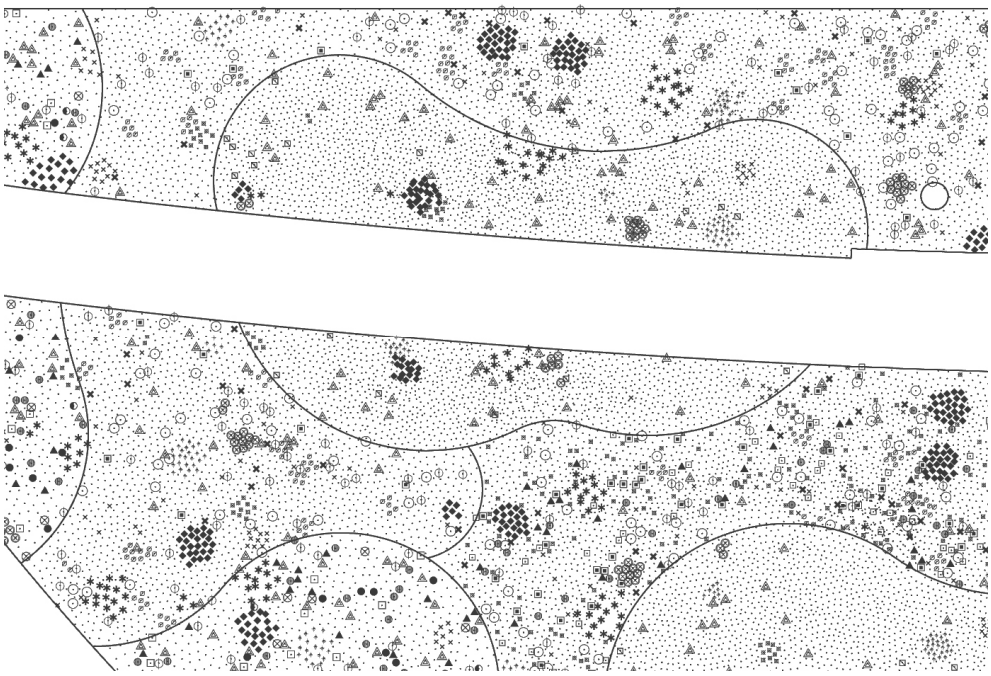

Fig. 3: Detailed planting plan in Autodesk Revit

and scale is not available, however it is expected to be significantly higher both in the initial design and any subsequent iterations or updates. A test on one planting area of 25 m²; 370 plants found manual placement required approximately 17 minutes to generate a rule-based layout, compared with 46 seconds using the proposed workflow. While limited in scope, this supports the expectation of faster iteration.

4 Discussion

The development and testing of a computational framework for planting design within a Landscape Information Model (LIM) highlight both the opportunities and current limitations of digitally mediated approaches to complex ecological design. The proposed system demonstrates that planting design, often marginalised in conventional BIM workflows, can be modelled as a dynamic, data-rich process rather than a static representational layer. By representing individual plants as discrete objects, the model enables detailed control over spatial structure, species distribution, and density, allowing a direct relationship between ecological intent and design output. This approach has a number of advantages over previous workflows including:

1) Containment within a single software means less manual update processes and lower risk of misalignment and inaccuracy.
2) Schedules and inputs are intuitively structured and easy to edit or update.
3) Native scheduling means that tables can easily have a consistent appearance and functionality with other documentation.
4) Plant instances can be used directly for rendering or expressing symbols.
5) WYSIWYG – each plant is represented directly as a single instance without abstraction or rounding errors.

The results suggest that computational methods can be applied to the design of complex naturalistic plantings, combining traditional methods with digital tools that increase efficiency and allow for data visualisations and rapid iteration. Agent-based distribution methods, when combined with traditional design logics such as matrices, drifts, and clusters, provide a framework for exploring multiple configurations with reduced manual effort. The capacity to visualise each plant as both a symbolic and three-dimensional entity supports iterative feedback between designer intent, ecological patterning, and constructability. However, this study does not assess whether generated distributions approximate natural community structures beyond producing design-oriented naturalistic patterns. This approach also offers potential benefits for project communication and documentation, as design information can be transferred more consistently into implementation and maintenance workflows.

However, the findings also underscore the need for continued development of user-friendly tools and interfaces tailored to planting design practice. Current BIM environments remain limited in their capacity to handle complex, densely populated models. Future work should explore how such frameworks can integrate temporal dynamics, enabling simulation of growth and seasonal change, and how they might support design education by making the processes of planting design more explicit and interactive.

5 Conclusion and Outlook

This study demonstrates the feasibility and value of using a Landscape Information Model to support the virtual design and documentation of complex naturalistic planting schemes. By representing each plant as an individual object and integrating computational distribution methods, the proposed workflow bridges the gap between complexity and practical design implementation. The results indicate that digital tools can extend the expressive and analytical capacities of planting design, offering new ways to visualise, test, and communicate diversity and spatial structure. However, further refinement is required to improve interoperability, streamline user interfaces, and embed ecological parameters more deeply within design processes. While it is challenging to directly compare efficiency in live projects given the time investment in planting documentation for each project, trialling a site with areas documented using multiple methods would provide more robust comparison. This methodology is currently being applied on a major public project, which will provide a useful case study and further feedback on its application. Future research will examine the application of this methodology in teaching environments, where it may serve as both a design and learning tool to enhance understanding of composition, ecology, and digital practice in contemporary landscape architecture.

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Large Scale 3D Scanning as an Interactive Teaching Approach in Built Environment Disciplines

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Abstract: Virtual Site Visits (VSV) are used to approximate site visits where in-person visits are infeasible. Typical VSV rely on photography, videos and 360-degree images. With these methods, the creator must choose what to capture and from where to capture it, reducing the independence of subsequent analysis. 3D scanning methods, often used to create highly detailed replicas of small objects, can also create large scale scans of sites, eliminating the need for predetermined signposting or choice of shot. We describe a large-scale 3D scanning method to capture informal settlement areas in Bandung, Indonesia. Outputs from this capture method were surprising, revealing cultural and physical details not initially evident. Students can inhabit the 3D scanned space as they explore, from wide shots where slope and scale are evident, to narrow and close spaces where the lived experience can be felt. This can create an immersive study experience for built environment students.

Keywords: 3D Scanning, built environment, large scale, virtual site visits

1 Introduction

Virtual site visits (VSV) have emerged as valuable pedagogical tools across various educational contexts (TREGLOAN et al. 2023, KLIPPEL et al. 2019). Educators have employed them to provide students with access to environments that would otherwise be difficult or impossible to visit in person, places such as dangerous construction zones (EIRIS et al. 2021) or protected heritage locations (KOSMAS et al. 2020). They have also been designed to offer students flexible, on-demand access to site-specific information within its spatial context (WALLS 2021).

Much of this work is focused on captured reality approaches, which often include high-resolution 360-degree panoramic views alongside standard photographs taken on site, and recorded videos of experts explaining various processes and material components of site (QUINN et al. 2019). The strength of captured reality technology lies in its use of authentic site imagery and footage, however, because the content is already captured and has been organised by the creator, students have limited freedom to explore independently. This results in a more passive learning experience (PHAM et al. 2018).

Established spatial data capture has been explored most through high resolution scans of small objects for archiving purposes (LI et al. 2023, PIRAS et al. 2024). Mobile-based 3D scanning apps are increasingly common in undergraduate architecture education, enabling students progressing from traditional drafting to hands on digital data collection on site (ÁLVAREZ et al. 2025). It also allows students to quickly test design proposals in 3D environments starting from sketch physical models. Similarly, 3D scanning is used to produce models of cultural heritage artifacts allowing students the opportunity to spend time with artifacts that they may not be able to access in real life (REMONDINO 2011). The strength in

these models is in the detail of the scan, including scale, colour and materiality (BARSZCC et al. 2023) and how closely they simulate specific objects.

In contrast spatial data capture at large scale is an emerging field. While tested earlier, it was limited by lower resolution and technology constraints (HAALA et al. 2008). Recent advances have made this approach more viable and applicable, largely because the technology to combine scans from different systems is only recently becoming well understood, access to the correct equipment is only just now becoming affordable and the people with the skills to undertake this work are rare. However, spatial data capture methods represent a potentially more immersive experience for students because the scan is made of the space or area wholistically and potentially seamlessly, meaning that the creator does not necessarily need to choose, frame or highlight specifics angles (BARSZCZ et al. 2023, FANG et al. 2025).

Although research has established the efficacy of virtual learning environments across disciplines such as medicine and engineering (TREGLOAN et al. 2024), their application within built environment education remains underexplored, but the development of digital site recording and spatial data capture methods has the potential to transform design methods and teaching for the built environment, particularly when recording physical and environmental characteristics of space in urban environments (GREENE & WALLS 2023, LANGENHEIM & WHITE 2022).

This paper presents a case study of 3D scanning output of an informal settlement, captured using drone-based photogrammetry and terrestrial LiDAR scanners to recreate spaces in Bandung, Indonesia. Informal settlements, commonly known as *kampungs* in Indonesia, represent a significant and enduring feature of the country's urban landscape, housing a substantial portion of the urban population (KENT et al. 2022). The focus on the Tamansari sub-district. Tamansari is located in Bandung Wetan sub-district, approximately 3.3 km from Central Bandung. Tamansari also has the largest sub-district population, with 22,553 inhabitants.

Understanding informal settlements like Indonesia's *kampungs* is essential for developing cultural competence, place-based learning, and global perspective (JONES 2019). Informal settlements house nearly one billion people worldwide and represent the reality of how the majority of future urban growth will occur (SHIRLEYANA 2022). Built environment students must be given the resources to move beyond sanitised case studies to engage with the lived experiences, adaptive strategies, and community resilience embedded in these environments. Of particular note for our case study is that the informal settlements captured do not have street view options in Google Maps or other global satellite capture maps, and thus no other virtual opportunity exists to interrogate them at this level of detail.

2 Methodology

2.1 Site Selection

The Bandung *kampung* was selected as a location that fulfilled key criteria as an area for built environment learning. An initial workshop with informal settlement experts from Institute Technology Bandung (ITB), the University of Melbourne, and Hong Kong University was led by our research team and identified areas of opportunity and challenge in the urban environment, specifically the Tamansari Urban Village region. Based on the workshop discus-

sions, critical themes for on-site visual capture were identified, with focus areas including housing, public spaces, commercial areas, transport and infrastructure.

2.2 Equipment and Pre-field Planning

A Leica BLK360 terrestrial LiDAR scanner was selected for its compact form and portability, prioritising mobility over range and ultra-high precision. The scanner was mounted on a compact tripod at a constant height (~1.5 m) to simplify registration and maintain vertical consistency across scans.

Pre-field planning additionally considered the integration of complementary datasets, including 360-degree imagery and video-derived photogrammetry, and aerial drone capture, to address known limitations of terrestrial LiDAR in capturing roofs, upper facades, dynamic street conditions and broader environmental extents beyond ground-level line of sight.

2.3 Scanning Strategy and Data Capture

Scanning was conducted across a range of urban typologies, including narrow, open laneways (5–6 scans per segment), high street frontages (approximately 4 scans per elevation) and small, enclosed spaces (1–2 scans per space).

A high-overlap strategy (>40–50%) was maintained between adjacent scans to ensure robust registration and minimise drift. Short station spacing (5–8 m) was applied in constrained areas. To reduce occlusion, the scanner was offset laterally in a zigzag alignment rather than positioned along the centreline and was rotated around corners to maintain line-of-sight continuity.

The high degree of geometric and visual overlap, through features such as doors, poles, and facade corners eliminated the need for external registration targets.

2.4 Data Processing and Registration

Raw scan data was processed using Leica Cyclone REGISTER 360. Cloud-to-cloud registration based on point proximity was employed to align individual setups, resulting in minimal cumulative drift and vertical error. The consistent scanner height and high overlap contributed to stable registration across the dataset.

Following registration, the point cloud was cleaned and exported to CloudCompare for meshing and visualisation. A point-to-mesh workflow generated textured 3D models for enhanced interpretability and surface realism. The resulting 3D scenes were integrated into the Pedestal 3D platform to support object-based learning, visual analysis, and self-guided site exploration.

2.5 Multi-modal Data Combination

Terrestrial LiDAR data were combined with 360° imagery video-derived photogrammetry (processed in RealityScan), and drone photogrammetry. While LiDAR data acted as a primary geometric reference framework, image-derived datasets improved colour information and extended spatial coverage beyond scan extents, such as facade detail, roofs and upper levels and broader extent of the street inaccessible from ground-based scanning.

Together, these modes established a multi-scale continuous street-scale model and capture strategy combining metric accuracy, visual continuity and contextual completeness. These datasets were co-registered using iterative closest point (ICP) alignment and manual tie-point verification, resulting in a comprehensive unified model of the *kampung* environment suitable for subsequent analysis and pedagogical use.

3 Results and Discussion

3.1 Technical Challenges

Conducting laser scans in informal settlements presented multiple interconnected challenges. Initially, obtaining access required working with a local guide who had existing relationships with community leaders and residents. Without this crucial connection, researchers risked being perceived as outsiders or potential threats, which could have restricted access to the sites entirely.

The alleyways for the street transect scans are notably narrow yet serve multiple critical functions. They act simultaneously as transportation corridors, commercial zones, and residential spaces. This multifunctional nature meant constant pedestrian activity throughout the day. It was difficult to spend a lot of time capturing spatial information. To minimize disruptions, researchers strategically scheduled scans during early morning hours, before the sites became congested with daily activities. However, even during these quieter periods, the constrained spaces and ongoing foot traffic frequently interrupted the scanning process. As a result, it was necessary to rescan the same locations multiple times to capture complete and accurate data.

Data capture was conducted under mixed daylight conditions, with intermittent sunlight and variable pedestrian activity. Despite uneven and sloping terrain, the lightweight scanner facilitated stable positioning and re-levelling between setups. Some occlusion remained unavoidable within the densest portions of the settlement due to restricted access and obstructed sightlines.

3.2 Captured Data Outputs

Our intention was to use interactive 3D models to simulate an in-person field trip to expose students to local contexts. Through interactive 3D models, students were able to examine how residents navigate their local environment and daily challenges such as inadequate infrastructure and limited services.

The captured data outputs varied in scale and size and comprised large scale scans of street transects varying in length from 30m to 80m and up to heights of 10m (Figures 1–7).

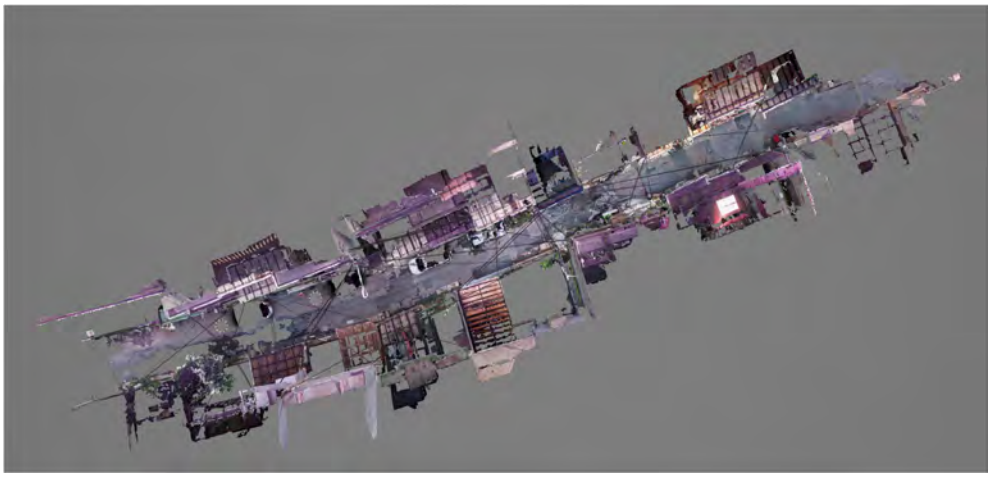

Fig. 1: Alley transect 1 – A top-down view including some rooftop detail and runs of power lines crisscrossing the street

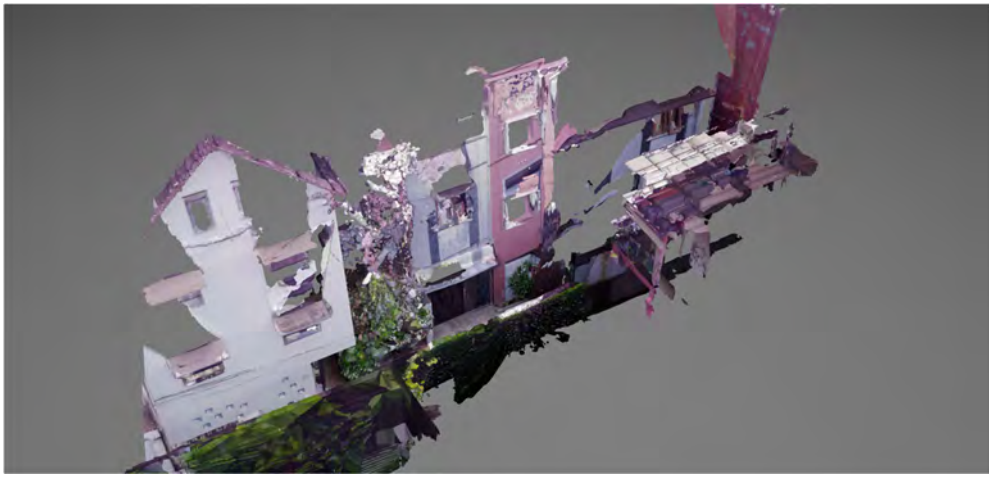

Fig. 2: Alley transect 2 – The highest point of the white building is 13m. From this view, with both sides of the alley built up, the alley itself is obscured.

3.3 Refining the Definition of Interactive 3D Models

KLIPPEL et al. (2019) identifies three distinct types of VSV. At the basic level, virtual environments mirror actual physical spaces, with users experiencing the same spatial limitations they would encounter during an in-person visit. The intermediate 'plus' level extends beyond physical constraints by offering viewpoints and comparisons unavailable in reality such as aerial perspectives or simultaneous views of buildings located far apart, while still maintaining representations grounded in physical space.

The Interactive 3D model method created in our examples aligns closely to the intermediate approach described above, but the model provides an experiential quality of depth and perspective change, giving the feel of a less manufactured environment than other methods (Figure 3 and Figure 4).

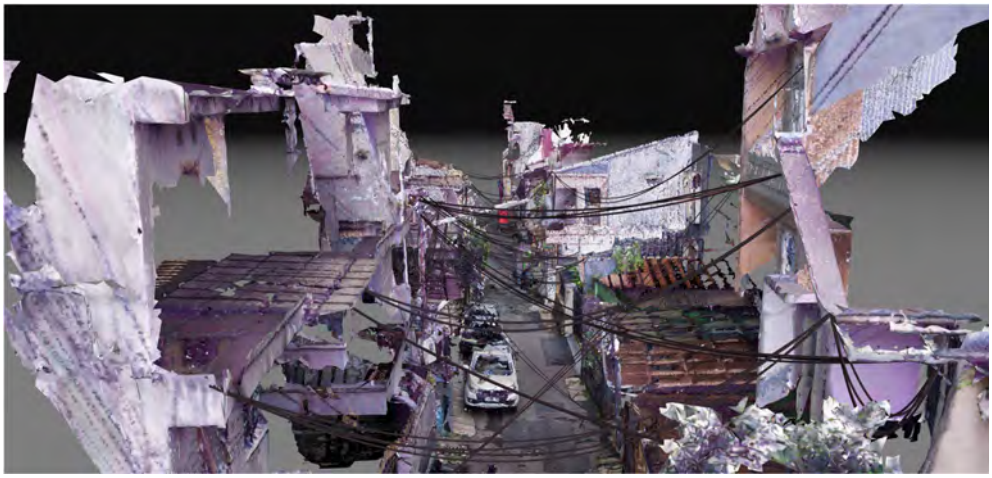

Fig. 3: Main Road transect – View down the main road with cars for scale showing how narrow the street is, as well as detail of powerlines and construction details of buildings

In addition, in our other paper (WALLS et al. 2025) we argue that void areas and occlusions offer insights into spatial variance and influence how a human subject might interpret the space, the gaps that illustrate areas that could not be seen and holes that show areas that are behind allowing a kind of digital extension of human perception that is made available through the artifact of the digital scan (ALVEAR 2020, IVANKOVIC-WATERS 2024).

This is evident in the scans made in Kampung. By working with the local conditions, particularly the small spaces of the streets and the fact that the alleyways are multifunctional in nature, and thus always busy, we have generated interactive 3D models that are less than perfect, reflecting the motion that exists. This quality becomes a texture of the space and reflects the way the space is lived in.

Further, as a result of the nature of the lidar capture and the conditions of capture, there exist elements of surprise as you examine the model. An example of this can be seen in the volleyball court scan (Figure 4), which at face value seems a typical space for exercise. However, by panning and moving through the space, students can discover small shops and a hidden seating area (Figure 5) with people watching the volleyball court from behind a netting.

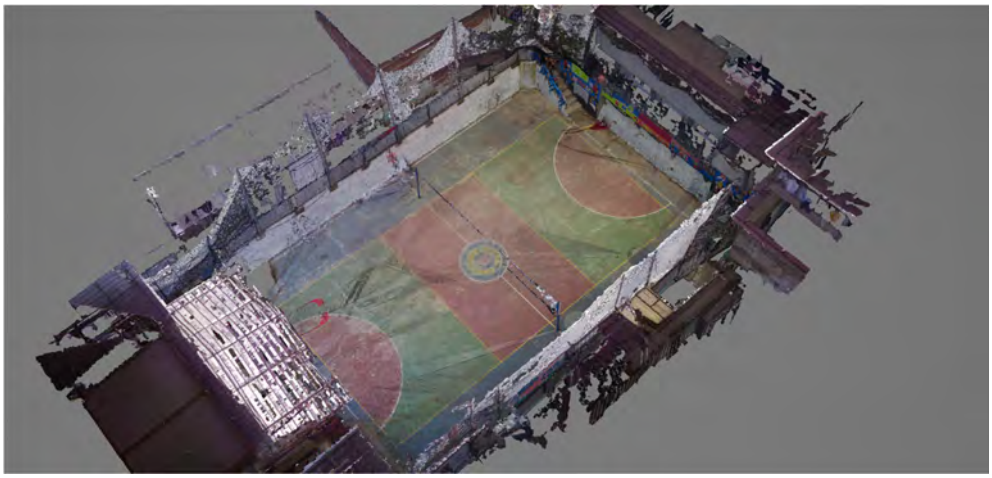

Fig. 4: Community volleyball court aerial view – Closer examination reveals details not visible here such as a hidden seating area (Figure 5)

Fig. 5: Community volleyball court seating area, including people and a small shop

The fragmented nature of the seating area scan presents an interesting opportunity for discovery through the output of the LiDAR scanning method. Although the seating space was not intentionally captured, it appears in the dataset, nonetheless. This differs from earlier technologies that required instructors to manually construct 3D models with predetermined scopes and intentions. The earlier approach often constrained students' exploration (MAGHOOL et al. 2018). The level of detail in such instructor-created models was typically dictated by specific learning objectives and the intended content of the virtual visit (LUCAS 2018, MAGHOOL et al. 2018). In contrast, the passive recording enabled by LiDAR scanning minimises subjective decisions about framing or composition in VSVs, allowing for a more objective spatial record. This objectivity gives subsequent viewers the freedom to interpret

and construct their own narratives within the captured environment. Consequently, the seating area and other partially rendered figures and objects become sites of discovery that enhance students' agency as they navigate the space.

Lastly, it has been shown that Virtual landscapes (VL) make accurate depth and slope perception difficult – by a figure of about 20% (CH'NG et al. 2016). Another advantage of these large-scale interactive 3D models is that they allow users to 'step out' of the landscape. For example, in the constricted space shown in Figure 6, where the low roof and lack of visibility around corner make it difficult to estimate distance, viewers can zoom out of the model and view it from a transect perspective (Figure 7) to better understand slope and profile. This is useful for understanding terrain, and something not possible in a VR environment or using photographs and 360 photographs.

Fig. 6: Inside view of Alley transect 4. The constricted space makes it hard to get a sense of depth and scale, equally it demonstrates the sense of enclosure residents would experience as they walked through there. For reference, this shot is taken from the green end of the transect in Figure 7.

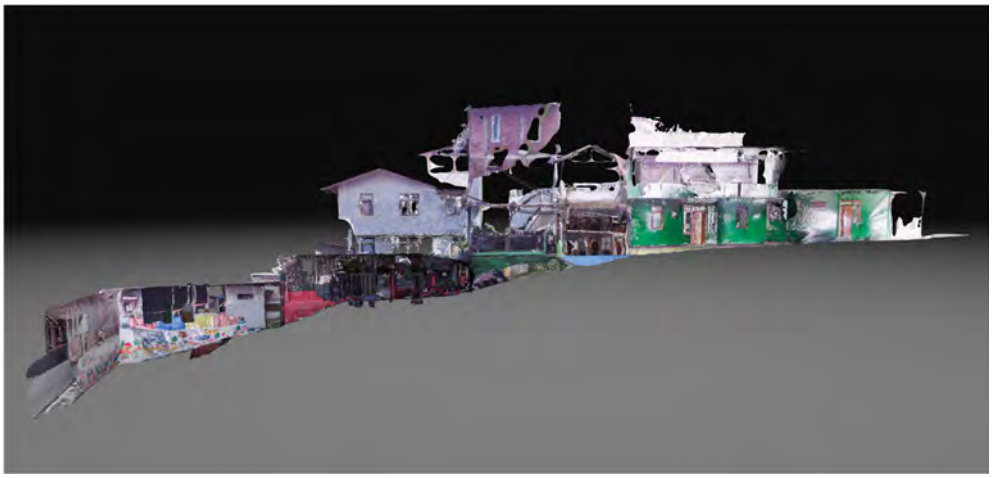

Fig. 7: Alley transect 4 – Providing a sense of the length of the space, but critically the slope of the alley from right to left as it bends to the left at the bottom, the user can investigate the space from many perspectives

This multi-scalar capability is valuable for developing critical urban analysis skills. Students can seamlessly zoom out to examine the broader neighbourhood fabric. The immersive nature of 3D visualization helps students who have never physically visited these communities to develop spatial empathy and contextual awareness.

Our experiential approach bridges the gap between abstract landscape theory (LEGACY 2017, JONES 2019) and the reality of how people inhabit these spaces. It encourages students to think critically about conventional planning methods that often overlook local knowledge and instead embrace community-centred approaches that lead to more resilient and contextually appropriate solutions.

4 Conclusion and Outlook

These 3D models function as part of a comprehensive suite of resources. The VSV additionally comprises an interactive map and include 360-degree videos that allow students to navigate through the alleyways and experience the spatial character of the settlement, interview content with community leaders, academics, and policymakers to gather detailed, place-based knowledge about key thematic issues and 3D laser-scanned models that provide detailed, explorable views of particular spots of interest. This combination enables students to both move through the broader environment and examine specific locations in depth.

Students' informal in class responses suggested that the 3D models promoted engagement, critical thinking, and self-led learning. Beyond simply observing narrow alleys and improvised structures, many students reflected on how residents creatively adapt limited spaces for multiple uses.

Technically, there is scope to refine the multi-method workflow. Improved drone coverage and overlap with scan areas and denser photogrammetric reconstructions could reduce occlusions to strengthen higher-level geometry. By combining multiple capture modalities within a single spatial framework, this research advances a model of VSV that privileges spatial agency and self-directed exploration over pre-determined framing.

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Radiant Landscapes: Painterly 3D Representations Using Gaussian Splatting

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Abstract: This paper explores 3D Gaussian Splatting (3DGS) as a method for artistic and analytical landscape representation, extending point clouds beyond geometric accuracy to convey painterly, volumetric, and immersive qualities of a site. Leveraging mobile-device capture, open-source 3DGS tools, and Blender-based visualization, the study demonstrates how dense vegetation, reflective surfaces, and subtle atmospheric effects can be represented – challenges that often exceed the capabilities of conventional LiDAR and Structure-from-Motion (SfM) methods. 3DGS encodes scenes as volumetric splats with color, opacity, and reflectivity attributes, producing renderings that are simultaneously impressionistic and photorealistic while enabling real-time navigation – even on modest hardware. The findings indicate that 3DGS transforms static 3D datasets into expressive, spatially coherent environments. It bridges traditional geometric documentation with perceptual and atmospheric insight.

Keywords: 3D Gaussian splatting, radiance-based modelling, immersive visualization, landscape representation

1 Introduction

1.1 Between the Objective and the Subjective: Radiance and Immersion

Perception of landscape operates across multiple scales. Observers focus on individual elements, such as plants or geological features, while simultaneously perceiving these elements as part of a broader relational field (SPUYBROEK 2014), embedded within a network of spatial, temporal, and atmospheric relationships. Immersion arises not from isolated objects, but from experiencing these interrelated qualities, forming a sense of wholeness.

Fig. 1: Point cloud computed using 3DGS from UAV imagery, rendered with variance in color and (A) uniform radii, (B) non-uniform radii, (C) non-uniform radii and variance in opacity | Images, 3DGS data processing & visualization: Marc-Eduard Ihle

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The notion of infinity – where background distance, sky, light, and atmospheric effects converge – is essential to creating immersive environments that engage the observer fully, allowing perception of spatial and material qualities beyond the purely visual.

Fig. 2: Nineteenth-century Romantic landscape painting: (A) Wanderer Above the Sea of Fog, oil on canvas, Hamburger Kunsthalle (FRIEDRICH 1818), (B) The Spell of the Arctic, oil on canvas, National Gallery, Oslo (BALKE 1870), (C) Valley of Aosta Snowstorm, Avalanche and Thunderstorm, oil on canvas, The Art Institute of Chicago (TURNER 1836)

Historically, representation of landscape has oscillated in its quality between measurable geometry and phenomenological experience. In ancient Greek and Roman practices, site assessment extended beyond topography and materials to include climate, orientation, and environmental suitability.

Fig. 3: Motion of the Sea: 30-second exposure capturing the flow, texture, and directional movement of the ocean | Foto: Marc-Eduard Ihle, 2017

Vitruvius, in *The Ten Books on Architecture* (VITRUVIUS 1914), emphasized that spatial quality arises not only from physical form but from the interactions of light, air, terrain, and human presence. Such relational criteria recognized the emergent, immersive qualities of place – an understanding later articulated as *Genius Loci*, or the spirit of place, which Christian Norberg-Schulz reframed as the perceptible, immaterial character of a site.

The nineteenth-century Romantic movement further amplified these atmospheric and relational dimensions. Artists such as Caspar David Friedrich, William Turner, and Peder Balke prioritized light, depth, and weather over strict topography, creating landscapes where form dissolved into radiance and immersive perception.

Photography and cinematography later extended these explorations, capturing time-based environmental forces – wind, water motion, cloud formation, and changing light – while maintaining immersive qualities akin to Romantic abstraction.

1.2 Beyond Objective Sensing and Representation

Documenting landscapes beyond strictly measurable criteria remains a challenge. Experiencing a site involves dynamic sensory and temporal qualities – light, wind, sound, seasonal change, and subtle relational interactions. Advances in radiance-based sensing, such as 3DGS, allow some of these visual environmental dynamics to be captured and digitally explored (YANG et al. 2024).

Fig. 4: Impressionistic representation of snow and slowly flowing meltwater, using 3D Gaussian Splatting (3DGS) to capture the granular texture of snow and the directional, blurred qualities of moving water | Student: Maja Broberg Røysland

Fig. 5: Student Work: Close-up 3DGS renderings of urban snow in a parking lot, highlighting pollution and texture, (A) (B) perspective projections, (C) orthographic projection | Image: Hedvig Riiser Hegge

Repeated image capture from identical viewpoints at different times of day and across seasons allows representation not only of geometry but also of temporal variation and environmental transformation. Arctic environments, for instance, demonstrate extreme seasonal contrasts, profoundly altering light regimes, vegetation visibility, snow cover, and hydrological dynamics. Experiencing such conditions requires temporal depth as much as spatial accuracy, highlighting how landscape perception extends beyond static geometry.

Traditional surveying methods, including LiDAR and Structure-from-Motion (SfM), focus primarily on geometric precision, often excluding atmospheric, volumetric, and ephemeral qualities. Dense vegetation, reflective surfaces, and diffuse light scattering remain challenging, and resulting datasets can be computationally heavy, limiting interactive use in educational or participatory design contexts. Emerging radiance-based methods such as Neural Radiance Fields (NeRF) and 3D Gaussian Splatting (3DGS) address these limitations. In particular, 3DGS converts point clouds into volumetric splats encoding colour, opacity, reflectivity, and directional light, enabling immersive, painterly interpretations while preserving spatial fidelity. By integrating these approaches within the continuum of representational practices – from classical site description and Romantic atmospheric painting to photography – they expand digital surveying, bridging geometric accuracy with perceptual depth and temporal awareness.

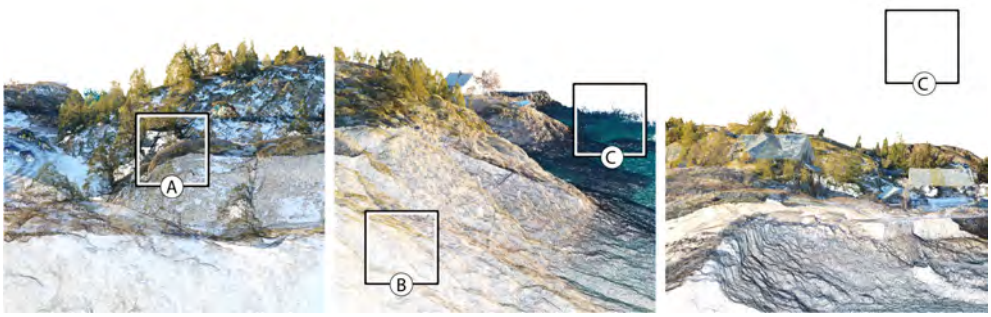

Fig. 6: *Digital Pointillism*, 2016: Point cloud generated via Structure from Motion (SfM) using *Pix4D Mapper* and UAV imagery, (A) Mixed point clusters, (B) Low point density / overly close, (C) Sparse or missing points / too far | Data processing: GRID-IT GmbH, Innsbruck | Drone Images & Visualization: Marc-Eduard Ihle

2 Expanding Digital Surveying

2.1 Point Clouds from LiDAR

LiDAR (Light Detection and Ranging) has long been employed for high-precision landscape capture, merging scientific rigor with expressive potential (IVSIC et al. 2021, IVSIC et al. 2022). Applications such as *Gotthard Landscape: The Unexpected View* reveal both visible and hidden landscape layers (VOLLMER et al. 2023), while the *Kyoto Garden Dialogues* use point clouds as media for exploring intangible qualities (VOLLMER et al. 2023). LiDAR ex-

cels in geometric precision, providing accurate sub-canopy data and reliable structural representation. Another benefit of LiDAR – particularly when the emitted pulse senses beyond human vision, such as in the Near-Infrared (NIR) range around 1064 nm – is the ability to assess vegetation (IHLE et al. 2024) by computing indices such as the Normalized Difference Vegetation Index (NDVI) or other vegetational indices.

Despite these advantages, practical limitations persist. High-end LiDAR systems are expensive and often inaccessible to students or small research teams. Environmental factors such as rain, fog, or reflective surfaces produce noisy or incomplete data. LiDAR point clouds are data-intensive, requiring substantial storage and processing power, and density decreases with distance, reducing legibility in expansive landscapes. Equipment size and operational complexity further limit participation, especially in educational or collaborative contexts.

Fig. 7: Point cloud rendered with spheres with a uniform radius of (A) 1mm, (B) 10mm, (C) 100 mm | 3DGS scan & visualization: Marc-Eduard Ihle

2.2 Structure-from-Motion (SfM)

Structure-from-Motion (SfM) offers a low-cost alternative, producing 3D point clouds from RGB imagery captured by drones, handheld cameras, or mobile phones. It captures color and texture, generating visually rich models that approximate human perception. SfM is particularly effective on static, matte surfaces such as rocks or soil, often producing pointillistic or painterly effects (WESTOBY et al. 2011). However, SfM shares some limitations with LiDAR. Reflective or refractive surfaces often cause feature-matching failures, while dense vegetation and atmospheric effects remain challenging to capture. SfM point clouds are typically less volumetric, limiting immersive interpretation. Nevertheless, the accessibility, portability, and ease of use of SfM make it an important complement to traditional surveying, particularly in educational settings or rapid field assessments.

2.3 From Uniform Voxels to Non-Uniform Splats

Rendering point clouds as voxels or other primitive shapes improves visual continuity (KANZLER et al. 2018) (Figure 7) but remains limited in volumetric or perceptual fidelity (WESTOVER 1991). 3D Gaussian Splatting (3DGS) refines this approach by representing each point as a volumetric splat encoding position, size, scale- and colour variance, opacity, and

reflectivity. Unlike static voxels, splats blend more seamlessly, especially when opacity attributes are applied to create photorealistic yet painterly images. 3DGS overcomes challenges inherent to both LiDAR and SfM.

Fig. 8: Using *Geometry Nodes* and *Shader Nodes* in *Blender* to manipulate point centered geometry: A) Cube (Voxel) with uniform scaling along X, Y, and Z, B) Cuboid with non-uniform Z-scaling based on slope angle, C) Parallelepiped aligned perpendicular to the surface normal, D) Parallelepiped perpendicular to the surface normal, with non-uniform scaling in the X and Y directions, E) Parallelepiped perpendicular to the surface normal, scaled in X and Y, and subdivided using a Catmull-Clark algorithm – representing a "splat" | Visualization: Marc-Eduard Ihle

2.4 Opportunities for Landscape Representation and 3DGS

While 3DGS has seen growing use in fields like robotics, heritage documentation, and agriculture (CHEN et al. 2022, LI et al. 2025, YU et al. 2025, ZHAO et al. 2025) its application within Landscape Architecture still remains rather underexplored.

Fig. 9: Point cloud computed using 3D Gaussian Splatting (3DGS) and a mobile phone with an RGB camera: Point Cloud rendered with (A) uniform radii, (B) uniform radii and variance in color, (C) non-uniform radii and variance in color and opacity | Image: Marc-Eduard Ihle

2.5 Technical Overview

Table 1: Comparison of LiDAR, SfM, NeRF, and 3D Gaussian Splatting for Landscape Representation (ATIK 2025, PETROVSKA et al. 2025)

Criterion	LiDAR	SfM	NeRF	3DGS
Sensing Modality	Active	Passive	Passive	Passive
Data Source	Laser pulses	RGB Images	RGB Images	RGB Images
Vegetation Representation	Good capture of sub-canopy	No capture of sub-canopy	Partial capture of sub-canopy	Partial capture of sub-canopy
Reflective / Transparent Materials	Poor: scattering, noise, data gaps	Poor: feature matching fails	Good: view-dependent reflections modelled	Very good: preserves lighting and reflections
Atmospheric	Limited	Limited	Very good	Very good
Volumetric	Limited	Limited	Very good	Very good
Accuracy	Very high	High (surface-dependent)	Moderate (some artifacts)	Moderate-high (SfM-dependent)
Photorealism	Low	Moderate	Very high	Very high
Processing Speed	Slow	Moderate-slow	Slow (training)	Fast (training)
Render Speed	Slow	Slow	Moderate	Fast
Hardware (during field operations)	Specialized, heavy equipment	Low-end, light weight	Low-end, light weight	Low-end, light weight
Cost	High	Low	Low	Low
Storage Size	Very large	Moderate	Low	Moderate
In-situ Results	No	Limited	No	Yes
Artistic use	Low	Moderate	High	Very high
Educational use	Limited	Good	Limited	Very good

Fig. 10: Student Work: 3D Gaussian Splatting (3DGS) rendering depicting snow, ice, water, and gravel, with a perspective extending beyond the water onto the gravel surface | Image: Sofie Shuyang Bjarkø

3DGS represents landscapes as collections of Gaussian primitives iteratively optimized in position, scale, shape, colour, and opacity. Rendered collectively, these splats form continuous environments capable of Novel View Synthesis (NVS), supporting perspectives not limited to human viewpoints (SCHOB et al. 2023). Unlike NeRF, which relies on computationally intensive ray marching and implicit scene representation (BLANC et al. 2025), 3DGS uses

explicit primitives and rasterization-based rendering, enabling real-time performance even on low-end devices (KERBL et al. 2023).

Although resulting in larger storage sizes compared to NeRF, training and processing times are shorter, and interactive exploration remains responsive (KERBL et al. 2023). 3DGS thereby provides both analytical and artistic affordances.

Fig. 11: 3D Gaussian Splatting (3DGS) rendering of a forest floor, illustrating variations in splat size, color, and opacity under adjusted lighting conditions in *Blender* | 3DGS scan & visualization: Marc-Eduard Ihle

3 Methods

The methodological workflow for this study was structured into four interrelated stages, encompassing capture, processing, manipulation, and integration of 3D Gaussian Splatting (3DGS) datasets. The aim was to explore both technical and artistic potentials of the approach while supporting pedagogical applications, with outputs disseminated as video sequences and partially as immersive VR experiences.

Fig. 12: Student work: 3D Gaussian Splatting (3DGS) representation of a forest clearing, capturing snow-covered ground, mossy surfaces, and trees in the background | Image: Line Waal Gjøsteen

3.1 Generation of 3DGS Datasets

The first stage involved capturing images of landscapes using multiple acquisition strategies. Three types of image sources were tested: (1) frames extracted from video sequences, also referred to as Multi-View Stereo (MVS), (2) overlapping photographs captured with mobile phones using Structure-from-Motion (SfM) applications, specifically the *3D Scanner App*, and (3) manual photographs taken with a DSLR camera equipped with a 35mm lens.

These images were then processed through three computational workflows to generate point clouds: desktop-based *COLMAP*, the locally installed *Postshot* 3DGS application, and the mobile *Scaniverse* app, which computes 3DGS splats in real time during capture.

The outputs from these workflows were exported as .PLY files (Polygon File Format/Stanford Triangle Format), containing point cloud attributes such as position, colour, opacity, scale, rotation, and spherical harmonics coefficients. These attributes formed the foundation for further analysis, artistic manipulation, and immersive visualization.

3.2 Blender Integration and Scene Building

In the second stage, 3DGS datasets were imported into *Blender* for visualization and further manipulation. Two *Blender* add-ons were employed: the *3D Gaussian Splatting* add-on (RESHOTAI 2025), which visualizes splats as spheres with adjustable attributes, and the *3DGS Render* add-on (KIRI-INNOVATION 2025), which renders splats as planes while offering similar attribute variability.

The *3DGS Render* add-on offered more advanced functionality. However, its slower performance and complexity limited rapid experimentation, particularly in educational contexts. In both cases, *Geometry Nodes* and *Shader Nodes* were leveraged to manipulate splat attributes, including colour, size, orientation, and opacity, allowing for nuanced artistic and analytical control. *Blender*'s scene-building tools – lighting, depth of field, camera positioning, and modifiers – were then used to add individual interpretations.

Fig. 13: Student work: Still images extracted from a video sequence, Highlighting mushrooms on the humid floor of a spruce forest depicted using 3DGS | Image: Karolina Ciesluk

3.3 Node Trees and Splat Manipulation

The third stage emphasized the interpretive and educational potentials of 3DGS through the use of the pre-generated Node Trees by the add-ons mentioned above. These Node Trees allowed students to rapidly manipulate their scans without building complex node structures from scratch.

Shader Nodes complemented *Geometry Nodes*, enabling detailed control over transparency, colour blending, and material-like effects. By adjusting these parameters, students could enhance painterly, volumetric appearances creating renderings that were partly able to convey their emotional impressions experienced on site.

Fig. 14: Virtual Camera Settings: Altering the focal length (A) no f-stop, (B) f-stop 5.6, (C) F-stop 2.8 | 3DGS scan & visualization: Marc-Eduard Ihle

3.4 Immersive and Interactive Scene Construction

The final stage focused on constructing interactive and dynamic 3D landscape scenes. Students adjusted camera positions, focal lengths, lighting conditions, and environmental parameters in real time. The workflow enabled exploration from multiple perspectives, including novel and orthographic viewpoints that would not be possible with conventional photography or LiDAR capture.

In addition to still images, each student produced a 30-second video sequence incorporating animated camera movements. These sequences explored spatial transitions beyond typical human viewpoints, ranging from top-down orthographic projections to close-up zooms.

4 Results

Student workshops indicated that 3D Gaussian Splatting (3DGS) can be adopted relatively quickly, even by participants with limited or no prior experience in advanced visualization tools. Real-time interaction supported iterative experimentation and immediate evaluation of adjustments, which appeared to encourage sustained engagement. While the degree of interest varied among participants, most were able to produce coherent and navigable spatial reconstructions within a short timeframe.

When navigating their reconstructed digital environments, students generally reported a more intuitive perception of spatial depth compared to previous groups of students and explorations of traditional point-cloud viewers such as those found in GIS applications like *SagaGIS* or point-cloud editing software such as *CloudCompare*. The volumetric continuity of splats seemed to enhance spatial legibility and immersion, supporting a clearer understanding of relationships within the scene.

4.1 Capturing Vegetation and Reflective Surfaces

3DGS excelled particularly in photorealistic rendering of dense vegetation, including leaf- and stem-level complexity, canopy density, and atmospheric depth cues. Reflective surfaces especially characteristic of alpine and arctic winter environments – water, ice, snow – were represented continuously, overcoming scattering artifacts common in LiDAR and SfM. Volumetric depth and transparency allowed the visualization of diffuse or distant elements such as fog, open sky, or snowfields. This volumetric approach enabled a more holistic understanding of landscape structure, integrating near- and far-field elements in a perceptually coherent environment. Combined with NVS, users could explore landscapes from orthographic and unconventional perspectives, enhancing analytical and experiential comprehension.

4.2 Interpretive and Artistic Dimensions

As outlined in the introduction, 3DGS supports both analytical and artistic exploration by encoding volumetric, perceptual, and spatial qualities, which, in this study, enabled students to produce immersive renderings exploring these dual potentials.

Fig. 15: Student Work: 3DGS-based artistic representation of snow clusters forming within a marsh landscape | Image: Wattana Meethong

5 Towards Radiant Landscape Twins

The concept of the Digital Twin (DT) has been interpreted in multiple ways across disciplines (ABDELRAHMAN et al. 2025). In this paper, *Radiant Landscape Twins* are understood as landscape-specific digital twins generated through 3D Gaussian Splatting (3DGS), designed to integrate structural, perceptual, and atmospheric qualities within spatial-temporal, radiance-based environments.

Unlike conventional photogrammetry or LiDAR workflows, 3DGS retains phenomena typically treated as noise – such as fog, rain, snowfall, or distant sky conditions – while preserving spatial coherence. As a result, these twins function not merely as accurate geometric replicas but as dynamic, modifiable environments for analysis, design exploration, and narrative representation, enabling both analytical rigor and creative engagement.

Radiance encoding allows for nuanced depiction of colour, depth, and light scattering, bridging a gap between measured data and human perceptual experience. *Radiant Landscape Twins* thus facilitate immersive pedagogy, participatory design, and remote sensing applications, enabling exploration and understanding of environmental qualities that would otherwise require physical presence.

6 Discussion and Conclusion

6.1 Comparative Positioning

Compared to LiDAR and Structure-from-Motion (SfM), 3D Gaussian Splatting (3DGS) integrates volumetric rendering with real-time responsiveness. LiDAR remains superior for precise terrain mapping and vegetation penetration, while SfM continues to provide a valuable low-cost approach to photogrammetric reconstruction. Neural Radiance Fields (NeRFs) offer very high visual fidelity but typically require intensive computational resources and lengthy training times (ATIK 2025, BLANC et al. 2025).

3DGS occupies a middle ground, combining photorealistic rendering, volumetric encoding, and interactive efficiency (KERBL et al. 2023, YU et al. 2025). This balance of accessibility and expressive potential makes the technique particularly suitable for pedagogical environments. During the scanning phase, mobile workflows – especially those using smartphone applications such as *Scaniverse* – proved highly accessible, requiring minimal familiarization and enabling all students to participate actively in fieldwork.

Similarly, the subsequent digital design process using visual programming tools such as *Blender* and its node-based interface (IHLE et al. 2024) was comparatively easy for students to adopt, particularly when contrasted with the more technical user interfaces of less visually oriented software applications.

6.2 Outlook

Future developments may incorporate AI-assisted extrapolation, enhanced novel-view synthesis, and expanded multisensory data encoding (BLANC et al. 2025, YANG et al. 2024). As radiance-based modeling techniques mature, *Radiant Landscape Twins* could evolve into interactive research environments.

Augmented Reality (AR) could extend temporal awareness by overlaying seasonal or hypothetical conditions onto a site – for example, visualizing winter landscapes during summer, thus enabling a “digital landscape laboratory” for examining ecological processes, seasonal change, and potential climate impacts (VERSTRAETE et al. 2025).

Such frameworks may also open possibilities for more immersive and interpretive forms of conveying environmental evidence. By integrating data beyond the visible spectrum – such

as Near-Infrared (NIR) for vegetation analysis or Thermal Infrared for surface temperature patterns – these models could make otherwise intangible or non-visible processes more perceptible to stakeholders and decision-makers. In this way, spectral, seasonal, and climatic variations might be experienced spatially rather than solely interpreted through abstract diagrams or datasets.

This approach may prove particularly valuable in communicating conditions in remote or less accessible regions, including high Arctic landscapes or even extraterrestrial environments. Echoing Susan Schuppli's notion of "earth evidence," radiance-based twins might offer new ways of situating environmental data within experiential contexts. Such representations could potentially support more empathetic engagement with climate change scenarios and projected future impacts, complementing conventional quantitative forms of analysis rather than replacing them.

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A Comparative Review of BIM-Based Software in Landscape Design: Vectorworks vs Autodesk Revit

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Abstract: While Building Information Modelling (BIM) is widely adopted in architecture and engineering, its implementation in landscape architecture remains limited. This paper presents a comparative study of Autodesk Revit and Vectorworks, evaluating their suitability for Landscape Information Modelling (LIM). The comparison focuses on modelling techniques, data integration, and usability. Given the complexity of BIM software selection, a comprehensive evaluation framework was developed through literature review. To validate the findings from the literature review, expert interviews were conducted with BIM professionals in the landscape industry, and the collected data were analysed using the multi-criteria decision-making methods AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). The study aims to provide insights to enhance landscape modelling workflows and promote broader adoption of LIM within the profession.

Keywords: Landscape Information Modelling (LIM), Multi-Criteria Decision Making (MCDM), Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

1 Introduction

With the rapid expansion of urban spaces and the increasing demand for large-scale housing developments, the importance of landscape architecture / urban design within the construction industry cannot be overlooked (CHESHMEHZANGI 2018). However, the landscape sector within the construction community remains relatively slow in adopting Building Information Modelling (BIM) practices, especially compared to other disciplines within the Architecture, Engineering, and Construction (AEC) industry (NIKOLOGIANNI et al. 2022)

This hesitancy is often attributed to the limitations of current software tools, which are primarily designed to support building development rather than landscape-specific needs (NIKOLOGIANNI et al. 2022). As a result, tools for effective landscape modelling remain scarce, leaving landscape architects under equipped to fully embrace BIM workflows. The concept of Landscape Information Modelling (LIM) has emerged to address this gap, offering solutions tailored to the unique requirements of landscape architecture (AHMAD & ALIYU 2012). However, there is a significant lack of research and literature exploring LIM tools and their effectiveness in meeting landscape-specific needs (NIKOLOGIANNI et al. 2022). While many available software platforms prioritize architectural modelling, the specialized needs of landscape modelling, such as terrain, vegetation, and outdoor environments remain underexplored and insufficiently supported (BORKOWSKI & WYSZOMIRSKI 2021). The purpose of this research is to emphasize the importance of utilizing appropriate software tools for LIM and to examine how the current market software addresses specific needs. It aims to investigate the software requirements of landscape architects and analyse the key modelling elements involved in landscape architecture components during the modelling process.

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2 Background

2.1 BIM (Building Information Modelling) in Landscape Architecture

In professional landscape architecture practice, BIM is increasingly intersected with workflows that extend beyond traditional design tasks. Large scale projects now require landscape architects to coordinate with architects, engineers, and contractors in shared digital environments where interoperability is critical (BERLATO et al. 2025). BIM participation often means contributing to federated models, aligning grading plans with structural foundations, integrating planting schedules into project databases, and ensuring spatial data remains consistent across disciplines (BEACH et al. 2017).

While there is no single BIM standard dedicated exclusively to landscape architecture (BORKOWSKI & WYSZOMIRSKI 2021) broader frameworks such as ISO 19650, PAS 1192, and buildingSMART's IFC provide applicable guidance (ZHU 2024). Additionally, the book BIM for Landscape by the Landscape Institute (a UK professional body for landscape architecture) (LANDSCAPE INSTITUTE 2016) explains how BIM standards and workflows can be adapted for landscape practice, providing guidance on collaboration, information management, and project delivery.

2.2 Autodesk Revit and Vectorworks Landmark: Overview and Features

Autodesk Revit was originally developed in 1997 by Charles River Software, later renamed Revit Technology Corporation in 2000, before being acquired by Autodesk in 2002 (AUTODESK, INC. 2002). Revit addresses the growing challenges faced by the Architecture, Engineering, and Construction (AEC) industry, particularly those related to coordination, interdisciplinary communication, and change management within projects (MORENO et al. 2019). Unlike AutoCAD, which was based on 2D drafting workflows, Revit was developed as a purpose-built BIM platform. It provides an integrated, data-rich way to manage digital representations of a building's entire lifecycle, including materials, costs, and schedules, to support better decision-making and collaboration among project stakeholders (AUTODESK, INC. n. d.)

Vectorworks was originally developed in the mid-1980s by Diehl Graphsoft in the United States and was later acquired by the Nemetschek Group, a German parent company, in 2000 (VECTORWORKS, INC. n. d. [a]). Initially started as a general-purpose computer-aided design (CAD) platform, Vectorworks has progressively evolved into a comprehensive BIM software suite (ALTIERI 2024). Vectorworks Landmark is a module within the Vectorworks suite that supports landscape professionals by providing workflows for site modelling, hardscape and softscape design, sustainability analysis, and collaboration.

It is a BIM platform that supports every project phase, from pre-design and schematic design to construction documentation, integrating analysis of terrain, drainage, sustainability goals, and cost calculations within a single workflow. Distinguished by its broad interoperability, emerging technology integration, and powerful presentation tools, Landmark enables landscape professionals to design, collaborate, and deliver projects with efficiency and precision (VECTORWORKS, INC. n. d. [b])

2.3 BIM Software Selection and Evaluation

Autodesk Revit and Vectorworks Landmark were chosen for this study due to their strong market presence and distinct relevance to LIM. Industry surveys indicate that Autodesk Revit has emerged as the most widely used BIM platform in the AEC sector, with 50% of respondents identifying it as their primary design tool in the National BIM Report 2020 (NBS ENTERPRISES LTD n. d.). Its widespread adoption has positioned it as the de facto standard for integrated BIM architecture, engineering, and construction. In contrast, Vectorworks Landmark was recognized as one of the first few programs designed specifically for landscape architects, offering specialized tools such as GIS file import, a comprehensive plant database, intelligent planting design, refined hardscape and grading functions, and integrated site modelling with cut-and-fill calculations. According to (PIHLAK 2011), these features enabled landscape architects to produce data-rich, graphically accurate, and fully integrated 3D models, affirming the software's strength as a domain-specific solution

Additionally, comparative reviews from online platforms such as (CAPTERRA n. d.) and (TRUSTRADIUS n. d.) highlight Revit's strength in interdisciplinary BIM workflows and Landmark's usability for design-oriented, landscape-led modelling. Together, these tools represent the most powerful and widely referenced platforms available for BIM-based evaluation in the landscape architecture domain.

Selecting the most appropriate BIM software for landscape architecture projects presents a multidimensional challenge, often complicated by the lack of a universally applicable tool for all project phases. Scholars such as Mordue, Swaddle, and Philp (MORDUE 2016) and Sacks (SACKS 2025) argue that no single BIM platform can address the diverse needs across disciplines and stages of a project. This reality is particularly relevant in LIM, where specific tasks, such as terrain analysis, planting schemes, or site grading require highly specialized tools. The growing diversity of BIM platforms, coupled with overlapping functionalities and varying interoperability capacities, has made software selection increasingly complex (SINGH et al. 2011). To manage this complexity, Multi-Criteria Decision Making (MCDM) methodologies have been widely adopted to provide a structured and transparent decision framework.

2.4 Multi-Criteria Decision Making (MCDM)

MCDM refers to a set of tools and techniques designed to assist in selecting among alternatives when multiple, and often conflicting, criteria must be evaluated simultaneously (TAHERDOOST & MADANCHIAN 2023). These methods allow the integration of qualitative expert judgment with quantitative performance indicators, making them highly applicable in technology selection scenarios. Among MCDM techniques, the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are chosen due to their ability to assign weights to evaluation criteria and rank alternatives accordingly. In LIM applications, this dual-method approach is especially beneficial, as it supports informed decision-making by converting subjective expert input into objective, replicable data structures. Thus, using MCDM techniques not only enhances the transparency and traceability of the evaluation process but also ensures that the selected software aligns closely with both professional priorities and technical requirements.

2.5 Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The Analytical Hierarchy Process (AHP) is a well-established MCDM method that decomposes complex decision problems into a hierarchical structure comprising goals, criteria, subcriteria, and alternatives. It employs pairwise comparisons to derive numerical weights, ensuring accountability and consistency in expert judgments (SAATY 2001). The AHP method was adopted as it enables decision-makers to capture relative importance while ensuring that the weights reflect a broad range of expert perspectives for more reliable decision-making (DE FELICE & PETRILLO 2019). In a study by Aladayleh and Aladaileh applied AHP to BIM-based risk management, showing its value in prioritizing strategies and using sensitivity analysis to examine the shifting importance of financial, sustainability, and time-related considerations (ALADAYLEH & ALADAILEH 2024). By converting subjective assessments into quantifiable results, AHP provides a transparent, systematic foundation for subsequent ranking methods, making it especially valuable for this LIM-based comparison of BIM tools.

TOPSIS is an MCDM method introduced by (TZENG & HUANG 2011) in 1981 that ranks alternatives based on their distance from an ideal and a negative-ideal solution. The ideal solution represents the best possible performance across all criteria, while the negative ideal corresponds to the worst. By calculating the geometric distance of each alternative to these two reference points, TOPSIS determines a closeness coefficient that reflects how close an option is to the ideal (SHIH & OLSON 2022). This ranking approach is intuitive and effective, especially when combined with weighted criteria, such as those obtained from AHP (SHARMA et al. 2020). Nursal, Omar, and Nawi (2015) showed that TOPSIS can effectively support BIM software selection by providing a structured process to evaluate multiple criteria and rank alternatives through a web-based system (NURSAL et al. 2015)

2.6 Software Selection by Establishing Evaluation Criteria and Benchmarks

A Norwegian standardization project on BIM for landscape design provided a foundational framework, identifying 38 essential components used in landscape modelling. These elements include terrain features, vegetation types, outdoor furnishings, and structural elements, serving as benchmarks for evaluating BIM tools in landscape architecture (WIK et al. 2018). In a related study, researchers from the Warsaw University of Life Sciences emphasized the integration of GIS in LIM by identifying 14 core elements suitable for modelling within geomatics and land management contexts (BORKOWSKI & WYSZOMIRSKI 2021). Additionally, (ZAHRÁDKOVÁ & ACHTEN 2015) classified landscape elements into a structured information model, delineating them by function and spatial hierarchy within the BIM framework, contributing to a clearer understanding of LIM-specific object types and relationships

An analysis of existing standards and previous studies informed the development of a unified set of modelling benchmarks, representing key landscape components essential to effective LIM. This unified list served as the basis for expert interviews / survey, during which participants were asked to assess the relevance and practical implementation of each component. Insights gathered from these interviews were then used to validate and refine the benchmarks for use in the final evaluation.

3 Research Design

3.1 Research Objectives

- Objective I: To identify and analyse the key landscape architecture components and modelling elements essential for effective LIM
- Objective II: To evaluate and compare the capabilities of Autodesk Revit and Vectorworks in supporting the specific requirements of LIM
- Objective III: To assess the strengths and limitations of both software tools in addressing landscape architects' needs and provide recommendations for software selection in landscape design projects.

3.2 Methodological Framework

This study adopts the Plan-Act-Observe-Reflect (PAOR) framework (COHEN et al. 2007) to systematically evaluate Autodesk Revit and Vectorworks for LIM, integrating both qualitative and quantitative approaches through MCDM methods and expert consultation.

- Plan – The study commenced by clearly defining research objectives and establishing evaluation criteria for LIM, drawing on prior academic frameworks and domain-specific modelling requirements.
- Act – Primary data was collected through expert interviews and survey questionnaire, with AHP and TOPSIS methodologies applied to enable structured multi-criteria evaluation of the selected tools.
- Observe – Collected data were analysed both thematically and quantitatively. Validations were observed and reflected to ensure robustness and reliability of those outcomes.
- Reflect – The findings were synthesized to interpret the comparative performance of Revit and Vectorworks, assess the methodological framework, and develop practical recommendations for BIM adoption in landscape architecture.

4 Data Management/Analysis

The research area of LIM remains highly specialized within the broader discipline of BIM, as conventional CAD-based workflows continue to dominate much of landscape practice. This niche nature of the field posed a significant challenge in participant recruitment. Purposive sampling was therefore employed to ensure the inclusion of participants. The eligibility criteria were as follows:

- Participants must possess a minimum of three years of professional experience using either Autodesk Revit, Vectorworks Landmark, or both.
- Participants must have at least three years of professional experience working as landscape architects.

This criterion was designed to ensure that insights were drawn from practitioners with sufficient exposure to BIM-based tools and their practical applications in landscape workflows. Despite the recruitment challenges to this niche domain, a total of ten expert participants were successfully engaged. Of these, five were experienced primarily in Autodesk Revit, four were experienced primarily in Vectorworks Landmark, and one participant had stronger prior

experience in Vectorworks Landmark but more recent experience working with Autodesk Revit. Interviews were semi-structured in nature and ranged between 45 minutes to one hour in duration. Three interviews were conducted in person, while seven were carried out via online conferencing tools to accommodate geographical and scheduling constraints.

4.1 Interview/Survey Design

Data were collected using a structured questionnaire to guide the semi-structured interviews and systematically record responses. Ethical approval was obtained prior to the study. Participants were provided with a consent form and signed it to confirm their agreement to take part in the survey. A short presentation explained the study aims and evaluation categories, after which participants completed the survey to inform the interview discussion. The questionnaire consisted of four main sections

4.1.1 General Information (Section 1)

This section gathered contextual data on participants' professional background, including their role in landscape architecture, years of experience, and the primary BIM software used.

4.1.2 AHP Pairwise Comparisons (Section 2)

This section was designed to capture the relative importance of seven defined benchmark categories in LIM (e. g., Hardscape and Surfaces, Vegetation and Green Infrastructure, Terrain and Landform, etc). Using the Saaty 1-9 scale, participants compared categories in pairs, enabling the calculation of priority weights through the AHP.

4.1.3 TOPSIS Ratings (Section 3)

This section collected performance ratings for Autodesk Revit and Vectorworks Landmark across detailed sub-criteria within each benchmark category (e. g., pathways, green roofs, stormwater systems). Ratings were given on a five-point Likert scale ranging from "Very poor" to "Excellent," forming the quantitative dataset for the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) analysis.

4.1.4 Additional Feedback (Section 4)

This final section invited open-ended responses to capture qualitative insights, such as perceived strengths or weaknesses of each software, suggestions for missing components, and preferences for future use in LIM workflows.

4.2 Categories

Through literature review and analysis, the seven categories of the modelling elements were identified and their subcategories were refined as follows:

Category Name	Main Elements Included
Hardscape and Surfaces	Paved areas, roads, pathways, stairs, ramps, retaining walls, fencing, kerbs, railings
Vegetation and Green Infrastructure	Trees, shrubs, hedges, lawns, planting beds, green roofs, green walls, irrigation systems

Terrain and Landform	Topography, grading, slopes, cut-and-fill areas, soil conditions
Site Structures and Furniture	Benches, bins, lighting, signage, shelters, gazebos, pergolas, playground equipment
Water and Drainage Systems	Fountains, ponds, stormwater systems, culverts, bioswales, rain gardens
Functional Areas and Data Representation	Activity zones, circulation areas, property boundaries, zoning limits, accessibility routes, Sheets layout, Filters etc
Utilities and Subsurface	Electrical lines, communication lines, plumbing systems, underground infrastructure mapping

4.3 AHP Based Weight Derivation

The Analytic Hierarchy Process (AHP) was employed to determine the relative weights of key landscape categories that inform the multi-criteria decision-making framework. The procedure followed the structured approach proposed by (SAATY 2001) encompassing pairwise comparisons, normalization of the decision matrix, computation of priority weights, and evaluation of consistency. The entire process was implemented in Microsoft Excel, with individual participant responses entered separately.

Participants were required to compare the importance of each category relative to another using Saaty's 9-point scale (1 = equal importance, 3 = moderate importance, 5 = strong importance, 7 = very strong importance, and 9 = extreme importance). Reciprocal values (e. g., 1/3, 1/5) were automatically generated for inverse comparisons to form the pairwise comparison matrix.

The pairwise comparison matrix A was generated by assigning relative importance values to each criterion against all others using the Saaty scale. The structure of this matrix is:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & a_{23} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & 1 & \dots \end{bmatrix} \quad (1)$$

Each value in the matrix was normalized by dividing it by the sum of its column:

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (2)$$

The priority weight for each criterion was obtained by averaging the normalized values of its row. These weights represent the relative significance of each category and sum to 1 (100%).

$$w_i = \frac{\sum_{j=1}^{n} n_{ij}}{n} \quad (3)$$

The weighted sum vector was computed by multiplying the original comparison matrix by the derived weight vector. The maximum eigenvalue (λ_{max}) was then calculated as:

$$\lambda_{max} = \frac{\sum\left(\frac{Aw_i}{w_i}\right)}{n} \tag{4}$$

The Consistency Index (CI) and the Consistency Ratio (CR) was determined, where RI is the Random Index value for a matrix of size n (e. g., RI=1.32 for n=7).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

During validation, two participants recorded CR values exceeding 20%, indicating inconsistency in their judgments. These participants were contacted to revise their inputs; one successfully corrected their matrices, while one dataset was discarded. As a result, the final analysis was based on nine validated participant datasets. Although Saaty's guideline suggests a CR threshold of 10%, several studies note that when more than six criteria are involved, CR values up to 20% are widely considered acceptable due to the complexity of expert comparisons (SALOMON & GOMES 2024, AMENTA et al. 2020). After conducting pairwise comparisons with nine participants, the normalized weights for each category were averaged to derive the final priority weights.

4.4 TOPSIS Ranking and Analysis

TOPSIS (SHIH & OLSON 2022) was applied to compare the performance of two BIM platforms, Revit and Vectorworks in modelling various landscape and infrastructural elements. The analysis incorporated stakeholder ratings of sub-criteria, combined with AHP-derived weights, to generate a comprehensive ranking of both software options.

A total of nine participants were involved in this stage: four evaluated Revit, four evaluated Vectorworks, and one participant provided ratings for both platforms, owing to prior experience with each. Participants rated each sub-criterion on a 1-5 scale, where 1 represented lowest representational capability and 5 represented highest. Sub-criteria were grouped under seven main categories.

For each platform, a decision matrix $X = [x_{ij}]$ was constructed, where x_{ij} represents the score assigned to alternative *i* (Revit or Vectorworks) for criterion *j* (e. g., hardscape, vegetation). The scores were aggregated across respondents for each software to form weighted averages. The decision matrix was normalized using vector normalization:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{7}$$

The normalized matrix was then multiplied by the AHP-derived weights of each criterion to reflect their relative importance:

$$v_{ij} = w_j \,.\, r_{ij} \tag{8}$$

The positive ideal solution (A^+) and negative ideal solution (A^-) were identified by selecting the maximum and minimum weighted normalized values for each criterion:

$$A^+ = \max(v_{ij}) \tag{9}$$

$$A^- = \min(v_{ij}) \tag{10}$$

Euclidean distances were computed for each alternative relative to the ideal and negative ideal solutions:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - A_j^+)^2} \tag{11}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - A_j^-)^2} \tag{12}$$

The closeness coefficient (CC_i) was calculated to rank the alternatives:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^+} \tag{13}$$

This process enabled a systematic evaluation of both software across all relevant criteria, providing a balanced view that integrates user experience with the relative importance of different design elements in landscape architecture, while ensuring that the final comparison was not solely based on subjective preferences but also grounded in a structured, quantitative framework that enhances the reliability and validity of the results.

5 Findings

The evaluation was conducted in three distinct stages to provide a complete comparison of Revit and Vectorworks in the context of landscape architecture. This layered approach allowed the study to first capture user perceptions, then incorporate the professional priorities of landscape architects, and finally combine these perspectives into a weighted multi-criteria decision-making framework.

5.1 Stage 1: Unweighted User Ratings

The first stage of analysis was based entirely on the raw average ratings provided by participants in Section 3 of the survey. At this stage, no weighting or prioritization of categories was applied, meaning that each category contributed equally to the final comparison.

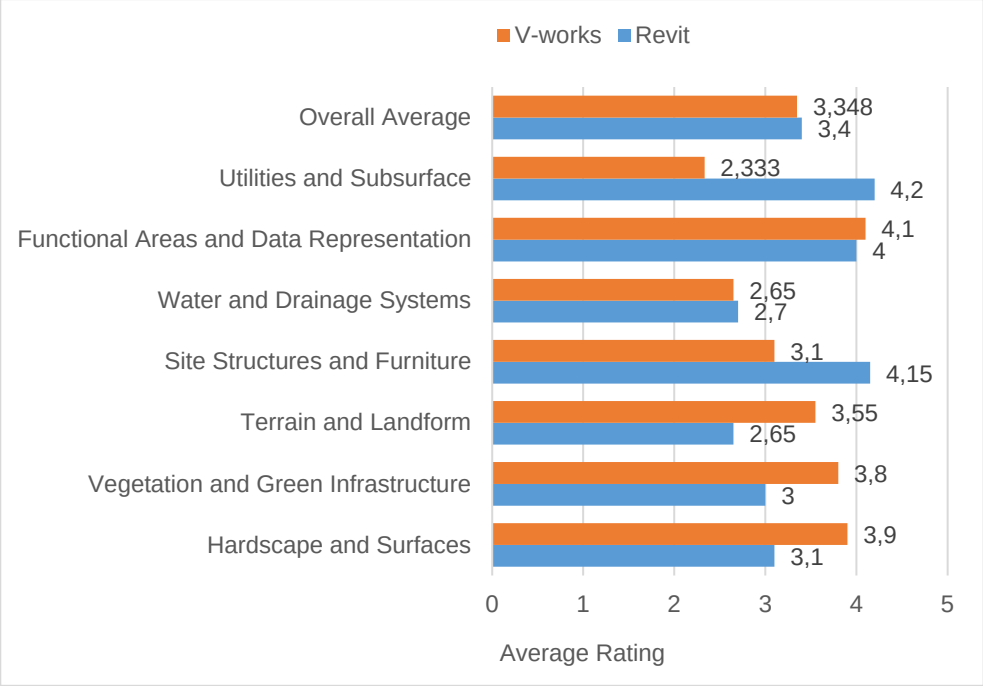

Fig. 1: Unweighted comparison of category ratings for Revit and Vectorworks

The results showed that Revit achieved its highest individual scores in Utilities and Subsurface (4.200), Site Structures and Furniture (4.150), and Functional Areas and Data Representation (4.000). These categories appear to be perceived as areas where Revit offers particularly strong capabilities according to user feedback. Vectorworks, on the other hand, received its strongest ratings in Vegetation and Green Infrastructure (3.800) and Hardscape and Surfaces (3.900), while also performing solid in Terrain and Landform (3.550). When all category scores were averaged, Revit recorded an overall mean score of 3.400, compared to 3.348 for Vectorworks. This suggests that in terms of general user satisfaction, and without considering the differing importance of each category, both software platforms deliver broadly comparable performance, with Revit holding a small numerical advantage.

5.2 Stage 2: AHP-Derived Weightage

The second stage introduced AHP weightings to account for the relative importance of each category from the perspective of professional landscape architects. Respondents were asked to make pairwise comparisons between the categories, and the resulting AHP calculations revealed a distinct hierarchy of importance.

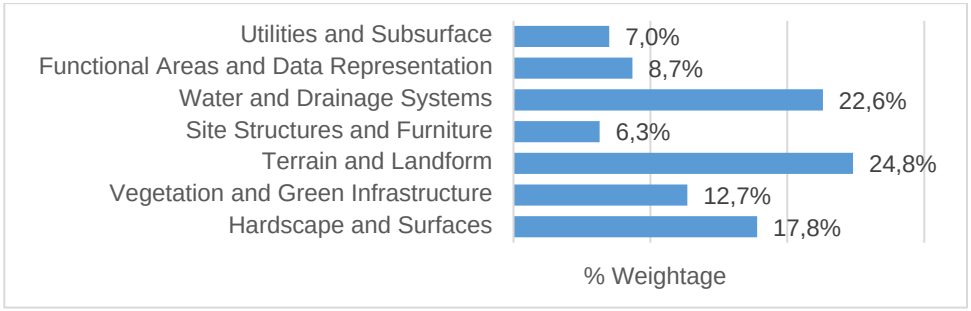

Fig. 2: AHP Category weighting distribution in percentage

Terrain and Landform emerged as the most critical factors, receiving a weight of 25%, while the lowest weights, 7% each were given to Site Structures and Furniture and Utilities and Subsurface. This weighting pattern indicates that features related to core site modelling and hydrological design are valued most highly, while elements such as furnishings and underground utilities, despite their importance in specific projects, are less influential in the overall evaluation. By shifting from equal treatment of categories to this importance-based framework, evaluation better reflect the priorities of the profession.

5.3 Stage 3 – AHP-Weighted TOPSIS Results

The third stage combined the category performance ratings with the AHP-derived weights and applied the TOPSIS.

In this weighted analysis, the rankings shifted noticeably compared to the unweighted results. This reversal can be explained by the fact that Vectorworks performs particularly strongly in Terrain and Landform and Hardscape and Surfaces, both of which have high weightings in the AHP model. Whereas Revit's strongest areas, such as Utilities and Subsurface and Site Structures and Furniture, carry relatively low weightings. Consequently, even though Revit performed well in several categories, those strengths had less influence on the final weighted score. The movement from Stage 1 to Stage 3 highlights the importance of integrating professional priorities into performance evaluation. Without weighting, the differences between Revit and Vectorworks appear small, and Revit shows a slight overall advantage. However, when the priorities of landscape architects are considered, the rankings change substantially, with Vectorworks emerging as the preferred option. Vectorworks achieved a CC of 0.742, placing it first overall, while Revit recorded a CC of 0.671, placing it second. This not only demonstrates the value of AHP in capturing subjective importance but also reveals how some categories, while performing well in raw terms, can have limited impact on the overall outcome if their professional relevance is lower. The shift also suggests that software selection decisions cannot rely solely on user satisfaction ratings, as these may not align with the functional areas that are critical.

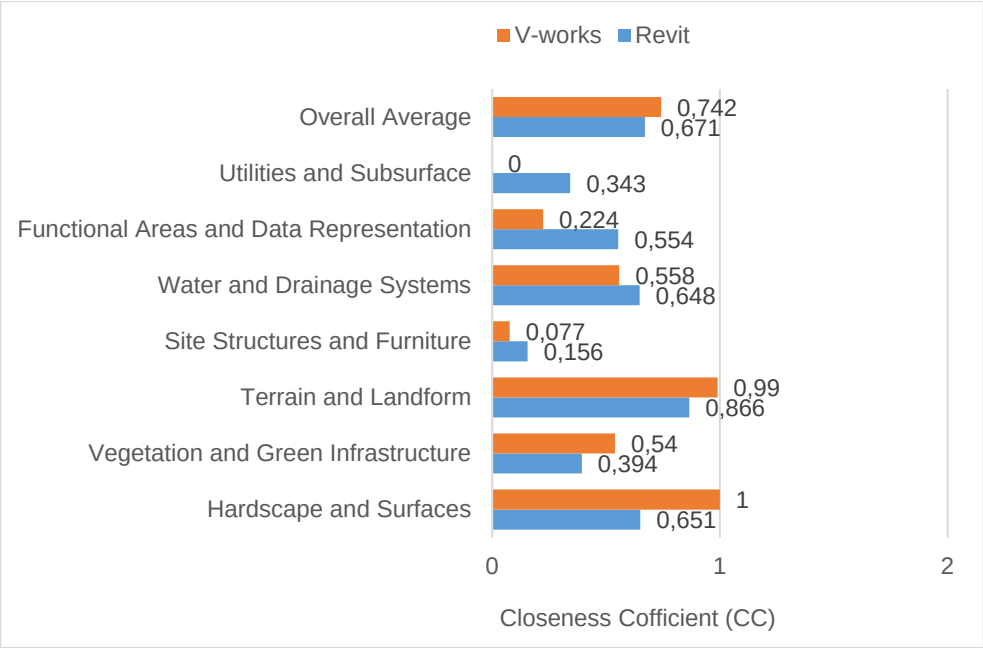

Fig. 3: Closeness Coefficient by Category

6 Discussions

6.1 Interpretation of Quantitative and Qualitative Results

Quantitatively, the Stage 1 results showed only small differences between the two platforms when evaluated using unweighted average ratings, with Revit achieving a slight numerical advantage overall. However, this changed once the AHP (Stage 2) and the AHP weighted TOPSIS method (Stage 3) were applied, which placed greater emphasis on the categories that professionals rated as most important. Qualitative feedback from survey participants adds important context to these quantitative results. A clear pattern emerged showing that participants' professional background, project type, and sector influenced how they prioritized the evaluation categories. For example, one Revit user who works as a landscape architect on large-scale data center projects placed the greatest emphasis on Utilities and Subsurface focus area that falls outside the priorities of most landscape architects but is critical for their specialized field. Another Revit user, whose works more on master planning prioritized Zones, Functional Areas and Data Representation, reflecting the importance of spatial organization and visual clarity at early design stages. Meanwhile, respondents engaged more heavily in construction documentation tended to assign greater importance to Hardscape and Surfaces, given its direct relevance to buildability and specification detail. This variation in professional priorities helps explain why some categories that scored highly in the raw average had relatively low influence in the weighted TOPSIS results.

Overall, this divergence between raw scores and weighted rankings underscores a central finding: a platform's perceived overall value is not determined solely by its average perfor-

mance, but by how well its strengths align with the dominant priorities of the individual profession. Revit continues to excel in technically detailed, infrastructure-oriented tasks, while Vectorworks aligns more closely with high-priority landscape design workflows.

6.2 Practical Implications for LIM Software Selection

The combined AHP-TOPSIS framework applied in this study highlights how the suitability of a LIM platform is not solely determined by general user satisfaction scores but is strongly influenced by the specific functional priorities of the intended project context. The results demonstrate that Vectorworks offer advantages in categories with high professional weighting such as Terrain and Landform and Hardscape and Surfaces, while Revit shows relative strengths in areas like Utilities and Subsurface and Site Structures and Furniture, which, although important, carry lower weighting in the aggregated professional priority model. These findings suggest that decision-makers should begin the software selection process by understanding the relative importance of functional categories in their project. Where projects demand topographical modelling, hydrological design, and hardscape representation, platforms excelling in those domains are likely to deliver greater overall value. Conversely, for projects where underground infrastructure modelling, subsurface utilities coordination, and furniture placement are central, software that performs strongly in those areas may be more appropriate.

6.3 Methodological Reflection

The methodology adopted in this study combined user satisfaction ratings, AHP weighting, and the TOPSIS to evaluate two BIM platforms in the context of landscape architecture. This multi-stage approach allowed for a layered analysis, beginning with raw user perceptions, progressing through the identification of professional priorities, and finally in a weighted multi-criteria ranking. One of the methodological strengths lies in the integration of both quantitative survey data and qualitative insights from interviews. This dual approach ensured that the evaluation considered not only numerical performance measures but also the practical realities and contextual factors that influence software adoption in the field. Furthermore, the use of AHP brought transparency to the process of determining category importance, while TOPSIS offered a structured and mathematically robust way of translating these priorities into comparative rankings. In the AHP stage, the weighting relied on subjective pairwise judgments, which can be influenced by participants' specific professional backgrounds, project types, and levels of familiarity with each platform.

In implementing AHP, the Consistency Ratio (CR) was kept below 20%, which exceeds the conventional 10% threshold recommended by Saaty. Several methodological sources note that CR values of up to 20% are acceptable for models with more than six criteria, provided the judgments are logically consistent and supported by qualitative context. While this adjustment allowed for the inclusion of all seven categories without overburdening participants, it does introduce some additional variability into the weighting process, a factor that should be considered when interpreting the results.

6.4 Limitations of the Study

While this research provides a structured comparison of Revit and Vectorworks for landscape modelling, several important aspects remain outside its scope. The study does not fully ad-

dress the dynamic ecological processes of landscapes, which unlike static buildings, are living systems that grow, evolve, and transform with seasonal changes, climate conditions, and long-term ecological succession.

Critical sustainability factors such as biodiversity net gain (BNG), carbon footprint assessments, and broader ecosystem service evaluations were also beyond the scope of this analysis, despite their increasing relevance in landscape practice and environmental policy. Similarly, interoperability and coordination challenges, particularly the integration of BIM platforms with GIS data, ecological modelling tools, and civil engineering systems were acknowledged but not examined in detail. These integrations are increasingly critical for large-scale, data-rich projects. The research was conducted in a niche professional area, which meant the participant pool was necessarily small: only nine individuals took part, with five datasets each for Revit and Vectorworks (including one participant who evaluated both platforms). Although this was sufficient for applying the combined AHP–TOPSIS framework, the small sample size constrains the statistical robustness of the findings.

These limitations highlight avenues for future research, particularly the need for holistic frameworks that combine dynamic ecological modelling with sustainability metrics and cross-disciplinary data coordination, enabling LIM to fully capture the living and evolving nature of outdoor environments.

7 Conclusion

This research shows that the suitability of BIM platforms for LIM depends less on the number of features they offer and more on how well they meet the specific needs of the discipline. By combining AHP derived weights with TOPSIS rankings, the study provides a practical method for evaluating software based on both performance and professional priorities. The results show that being widely used in general BIM workflows does not guarantee that a platform will be the best fit for landscape projects, where key functions, such as terrain modelling, water management, and hardscape design can influence the outcome.

The main contribution is a clear, priority-based evaluation process that can be adapted for other specialist BIM uses, helping to make software selection more transparent and better supported. For practice, the findings highlight the importance of defining functional needs before choosing a platform, focusing on how well it supports the essential outputs of landscape architecture. Beyond Revit and Vectorworks, this approach can help guide future choices as sustainability, ecological modelling, and data integration become a larger part of the profession.

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VR, AR and Immersive Visualization Technologies

Seeing Resilience: Evaluating 360-Degree Visualizations of Fire-Resilient Landscapes

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Abstract: Immersive visualization tools offer new opportunities for supporting community wildfire adaptation and landscape design. Using a case study from rural California, this paper evaluates 360-degree visualizations of fire-resilient landscapes developed with AI-assisted image editing. We assess the strengths, limitations, and ethical considerations of these tools through community engagement and interviews, demonstrating how site-specific visualizations can support understanding, dialogue, and decision-making around defensible space and wildfire resilience.

Keywords: Wildfire adaptation, defensible space, wildland-urban interface (WUI), virtual reality

1 Introduction

Wildfire risk is escalating across the globe (ELLIS et al. 2022). Nowhere is this more evident than in fire-prone regions such as California, where recent fire seasons have produced larger, faster-moving, and more destructive events that endanger human lives, critical infrastructure, and ecosystems (KEELEY & SYPHARD 2021, BALCH et al. 2024). This surge in catastrophic wildfire activity stems from a convergence of factors: land use expansion, altered landscape management, and a warming climate (MACDONALD et al. 2023). In California, rapid growth of the wildland–urban interface has heightened the likelihood of ignitions while exposing more communities and property to fire (RADELOFF et al. 2023). At the same time, widespread shifts in land and resource management since colonization have disrupted historical fire regimes, fundamentally changing how many ecosystems burn (STEEL et al. 2015). Climate change further amplifies these dynamics, creating hotter, drier, and longer fire seasons.

Given these challenges, the fields of landscape architecture and planning are critical actors in advancing fire resilience. Designers and planners not only shape the physical form of communities and landscapes but also work closely with residents, developers, and landowners navigating wildfire risk. Grounded in feminist science and technology studies and community-based research, we approach this work as an example of "situated" technological practice, where tools can extend what communities are able to see and collectively imagine (HARAWAY 1988, 2016), and where community-grounded methods for envisioning possible futures are increasingly essential in the face of rapidly deteriorating social-ecological resilience (ETIENNE 2014). Among the strategies available for reducing fire risk, fuel treatments – particularly the creation of defensible space through the selective thinning of vegetation and trees around structures – can reduce the likelihood that future wildfires will damage or destroy homes (MORITZ et al. 2022).

While residents in fire-prone areas are often supportive of risk reduction practices such as creating defensible space, several barriers can prevent them from taking action. Financial

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constraints are a major obstacle as many property owners struggle to secure the resources needed to hire contractors or purchase equipment for thinning vegetation. Physical ability presents another challenge, particularly for older residents or those without the capacity to undertake labor-intensive work themselves. Beyond these tangible constraints, there is also a perceptual barrier: it can be difficult for residents to imagine what their property will look like after vegetation is thinned. For some, uncertainty about the visual outcome can make them reluctant, especially when aesthetic, privacy, or cultural values are at stake. Another challenge is social dynamics: homeowners are more likely to mitigate when their neighbors do, so the absence of peer examples or community norms can dampen motivation (WARZINIACK et al. 2019). For many residents, hesitation is less about awareness of wildfire risk and more about difficulty imagining how mitigation measures will alter the lived experience of their property.

Compounding these challenges is a critical gap in the availability of adaptation-focused technologies that address local needs, priorities, or capacities. While innovation has accelerated in tools designed for wildfire detection, monitoring, and suppression, far fewer tools exist to support proactive mitigation and long-term adaptation (SCHLICKMAN 2025). A growing body of research suggests that immersive technologies can help bridge this gap. For example, a recent study demonstrates that 360-degree virtual tours can improve public understanding of how fuel treatments reduce fire hazards (TAYLOR et al. 2025). Yet, there is still a need for photorealistic, eye-level, site-specific visualizations that allow residents to directly engage with future landscape scenarios.

This study responds to the need for adaptation-focused tools by developing and evaluating a 360-degree visualization approach for fire-resilient landscapes. The tool provides residents with immersive before-and-after imagery showing how defensible space and fuel reduction treatments could transform their surroundings. Rather than introducing new technology, the study demonstrates a novel, community-facing application of existing visualization and AI-assisted tools that supports understanding, dialogue, and action around wildfire adaptation. We assess both the technical feasibility of generating these visualizations and their influence on community perceptions, decision-making, and willingness to implement fire-resilient practices. The work is part of the CAL FIRE-funded Tuolumne Community-Based Fire Resilience Project, which emphasizes collaborative, user-centered approaches to wildfire planning.

2 Methodology

Our study focused on properties in Tuolumne County, California, a rural region located in the Sierra Nevada, east of the Central Valley. The county faces a high risk of wildfire due to its dry climate, dense vegetation, and topography. Many residents live in the wildland-urban interface (WUI), where development meets undeveloped wildland, increasing both exposure and vulnerability to fire. Tuolumne County has a population of just over 50,000, with a large proportion of older adults and a mix of income levels, which can influence preparedness and recovery capacity. We implemented a community-based approach to testing the visualization tool: the initial interest in engaging landowners originated with local leaders, and testing the tools using imagery of participants' homes aimed to ground them in their own situated or contextual knowledge of place. We also studied not only how the tool affected their interest

in fire preparedness, but also their opinions about the tool's usability, grounding the results in community needs and preferences.

To refine our visualization approach prior to participant recruitment, we conducted several rounds of pre-testing using various types of imagery and tools. First, we sourced publicly available real estate photos of residential properties with overgrown vegetation. Vegetation removal decisions were guided by a retired CAL FIRE Battalion Chief with 30 years of experience using California Public Resources Code (PRC) 4291, the standard framework used statewide to assess defensible space and structure exposure in the wildland-urban interface. This reflects the same criteria typically used by fire professionals during property assessments and compliance inspections and was intentionally chosen to mirror real-world practice. While different fire professionals might develop somewhat different vegetation removal prescriptions for the same property, our goal here was not to produce a definitive "perfect" prescription but to generate a realistic, practitioner-informed set of decisions suitable for testing the tool under credible field conditions.

Using Adobe Photoshop's generative AI feature, we digitally removed this vegetation to simulate a thinned site. We then tested the same process using 360-degree imagery captured at Foothill Horizons Outdoor Education School, where vegetation thinning was being planned. After generating modified images in Photoshop, we brought school staff to the site and used Google Cardboard VR headsets to allow them to view and compare existing and treated conditions (Fig. 1). To explore residential contexts more fully and to test the ease of use of the image altering technology in residential contexts, we also captured 360-degree imagery at the homes of research team members, where structures were present. Photoshop was again used for vegetation removal, and we also tested Midjourney, an AI-powered image generation tool.

Fig. 1: Testing the visualization tool at Foothill Horizons Outdoor Education School

Participant recruitment was carried out in collaboration with a county-level Firewise coordinator. This individual distributed a flyer and study information to Firewise leaders across the country via email. We specifically sought residents of Firewise communities with untreated or minimally treated properties, as they were already aware of wildfire risks and likely to offer informed feedback. Twenty-one residents agreed to participate in the study.

The research team visited each of the 21 participating properties over a two-day period. These were primarily located in Sonora, Twain Harte, and Groveland, California. At each site, we captured 5 to 10 high-resolution 360-degree images using smart phones and the Teleport 360

app. Capturing multiple vantage points around each property allowed flexibility in later selecting the most effective viewpoint for visualization, and it also provided redundancy for instances when some images did not turn out as expected.

After reviewing the imagery, we selected one representative image per property that most clearly reflected the need for vegetation treatment. Using primarily Midjourney with some modification in Photoshop, we digitally removed vegetation to create a simulation of a thinned landscape. The amount and type of vegetation to remove was again guided by the retired CAL FIRE Battalion Chief to ensure consistency with defensible space and wildfire mitigation standards. Upon completion, each property owner received a private web link to view their original and modified 360-degree images side by side.

We conducted semi-structured follow-up interviews with 11 of the 21 participants after they had viewed the visualizations. These conversations explored their personal and professional experiences with wildfire, their perceptions of risk and resilience at the property level, and their impressions of the visualization tool. Participants provided insights on what worked well, what could be improved, and how the tool might be used in broader outreach or planning efforts. The open-ended format allowed for a wide range of perspectives, including suggestions for potential users and future improvements.

To gather broader feedback, we also hosted two community meetings following the individual interviews. These were held in Sonora and Groveland and were open to both participants and other local residents. Approximately 70 people attended the two sessions. During the meetings, we provided an overview of the larger CAL FIRE-supported project, showed sample 360-degree imagery and visualizations, shared preliminary findings from the interviews, and facilitated discussion on the tool's usability, limitations, and potential applications. As in the interviews, community members also offered ideas for alternative uses and additional audiences that could benefit from visualizations like the ones developed in this project.

3 Findings

3.1 Performance of AI-Assisted Visualization Tools

To start, we documented key insights about the performance of the AI-driven image-editing tools used to generate the visualizations. Each tool presented distinct strengths and limitations (Fig. 2). We also weighed community adoption: we prioritized tools that were cost-effective and simple to learn so a local organization could eventually take over maintenance and updates.

Midjourney struggled to handle dense, continuous vegetation effectively. Despite detailed prompts, it often replaced removed vegetation with similarly lush foliage, making it difficult to simulate realistic thinning. Its performance improved in scenes where vegetation was more isolated or distant from the camera, but it still tended to produce overly blended or stylized results in complex, greenery-dominated views. Notably, Midjourney excelled in scenes where architecture was prominent; it was able to generate convincing, cleaned-up renderings of homes by removing obstructions like trees, and its slightly stylized output, while sometimes cartoonish, occasionally helped draw attention to the areas that had been edited. Beyond performance, Midjourney was also significantly less expensive and easier to use than Photoshop, making it more accessible.

Photoshop, on the other hand, produced more photorealistic outcomes when successful, but it encountered its own challenges, particularly in preserving structure and perspective when buildings were involved. However, the newer "Remove" tool in Photoshop was especially effective for quickly eliminating specific vegetation elements, such as individual trees or clusters (Tab. 1).

Through this process, ethical considerations emerged. The use of AI-assisted tools raises questions of authorship, transparency, and embedded bias, particularly given that training datasets are proprietary and not fully disclosed. In this project, AI was used as a visualization aid rather than an analytic or predictive system, and its use was explicitly disclosed to participants. Nonetheless, these tools shape how future landscapes are represented and understood, underscoring the need for critical engagement with their limitations.

Fig. 2: Original photo without fuel treatment (top), Midjourney-edited image (middle), and Photoshop-edited image (bottom)

Table 1: Qualitative comparison of visualization tools

Criterion	Midjourney	Photoshop
Dense vegetation handling	Low	Medium-High
Performance near buildings	High	Medium
Photorealism	Medium	High
Ease of use	High	Medium
Cost / accessibility	High	Low
Adoption potential	High	Medium

3.2 Community Feedback and Practical Constraints

The interviews and community meetings surfaced a range of practical challenges, including difficulties capturing effective imagery, processing time in dense vegetation, unclear parcel boundaries, and inconsistent defensible space guidance.

Several participants noted logistical challenges in capturing effective 360-degree imagery, raising questions about where the camera should be positioned, which angles would best represent treatment needs, and who should be responsible for capturing or submitting the images. Once images were captured, processing time (particularly in areas with dense brush) was identified as a key bottleneck. Participants also pointed out the difficulty of visualizing treatments when parcel boundaries were unclear or when views and vegetation extended across property lines. Additionally, some expressed confusion about conflicting defensible space guidance.

Concerns about accessibility and equity also emerged. Participants emphasized that for those less comfortable with technology, the tool would need to be simple and intuitive to encourage adoption. We also noted difficulties for some participants in viewing the 360s through a web browser, indicating that still photos might be both more efficient to modify and more accessible to a wider audience. More broadly, while many valued the visualization, they stressed that the real cost (and the real barrier) is in doing the fuels reduction work itself, not generating imagery. Limited financial resources and labor capacity, especially among older or lower-income residents, were seen as critical constraints. Relatedly, some voiced frustration that neighboring properties left untreated could undermine their own efforts, limiting community-level fire resilience. Others expressed unease about the visibility of their properties through the tool, particularly considering growing concerns about how insurance companies might use imagery, even though aerial and street-view images are already publicly available. This is a tricky dynamic, and one way to work with this tension between privacy and utility could be to rely on principles of ‘data sovereignty’ – if the community themselves controls the imagery, that may be an option.

3.3 Opportunities for Tool Expansion and Community Use

In response to these challenges, participants proposed a wide range of tool modifications and feature enhancements. Many envisioned a more automated, user-friendly system, such as a mobile app that would allow residents to take their own photos and receive near-instant vegetation removal visualizations. Some suggested including a "ghost tree" feature in the post-treatment image to show where vegetation had been removed, or offering multiple treatment scenarios (e. g., 25%, 50%, 75% thinning) to better communicate phased or partial ap-

proaches. Additionally, many participants emphasized pairing these scenarios with estimated costs to inform budgeting and help prioritize phased implementation. Others advocated for more emotionally impactful content, such as visualizations of what the property might look like after a wildfire, to motivate action.

Suggestions also included more dynamic and interactive features, such as visualizing vegetation regrowth over time to illustrate long-term benefits or allowing users to "tap to remove" vegetation in real time through a phone or VR headset. Cost estimation tools, such as per-tree removal pricing or "add to cart" features, were also requested, particularly to support residents in budgeting or applying for grants. Participants further emphasized the importance of scaling the tool for neighborhood use, with the ability to visualize at a larger scale, including aerial views that provide context for the overall area.

Finally, participants expressed interest in layering additional information into the platform, including AR/VR compatibility, defensible space regulation overlays, contact lists for local contractors and programs, and species-specific plant guidance with flammability ratings and maintenance best practices. Some also suggested expanding the tool beyond homes to commercial lots, noting its broader potential for community wildfire resilience planning.

Across interviews and meetings, several themes emerged: visual clarity helped reduce hesitation, shared imagery supported community norms around mitigation, and tools were valued when they complemented, not replaced, local – situated – expertise. Participants framed the visualization less as an authority and more as a conversation starter that aligned understanding among residents, fire professionals, and neighbors, aligned with community-based technology development principles.

4 Conclusion

This study demonstrates how immersive, AI-assisted 360-degree visualizations can function as a practical, community-engaged design tool for wildfire adaptation. While the underlying technologies are not novel, their application in a participatory, site-specific context represents a meaningful contribution to digital landscape architecture and resilience planning.

By allowing residents to see potential future conditions of their own properties, the tool helped address perceptual and social barriers that often limit defensible space implementation. At the same time, the findings highlight important limitations, including reliance on qualitative assessment, the ethical implications of AI-generated imagery, and the need for complementary financial and labor support mechanisms.

Future research could build on this work through quantitative evaluation of behavior change, integration with cost and risk modeling, or longitudinal assessment of treatment adoption. For the JoDLA community, this project offers a transferable methodology for combining immersive visualization, AI-assisted workflows, and community engagement to address complex, place-based environmental challenges.

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Playful Complexity: Using a Serious Game with Immersive 3D Visualization to Balance Economy, Ecology, and Landscape Impact of Photovoltaic Plants

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Abstract: The transition to renewable energy is a balancing act: solutions should address both the climate crisis and the biodiversity crisis. At the same time, considering economical aspects, potential landscape impacts, and social acceptance patterns is crucial for success. This article presents an inter- and transdisciplinary approach for collaborative solar energy planning using a serious game combined with data-driven immersive 3D landscape visualizations. The process and results of connecting various interdisciplinary research outcomes and iteratively transforming them into a comprehensive game logic with corresponding visualization parameters are described. In the resulting game, players are challenged to achieve regional renewable energy targets by placing and configuring photovoltaic plants. Immediate feedback is provided for every action in the game regarding potential energy production, costs, and impacts on biodiversity, allowing an evaluation of potential impacts or synergies. 3D Visualizations also make it possible to assess the visual impact from any desired viewpoint. A total of five stakeholder workshops serves as the evaluation for this serious game. The workshop outcomes suggest that the presented strategy of developing a serious game as part of an interdisciplinary research project can aid in the communication and integration of scientific results. The resulting game impacted the decisions made by the stakeholders within the workshops, with most groups making a conscious effort to keep the biodiversity impact positive while also reaching the energy production target. Serious games such as this one could also be developed for similarly controversial landscape development processes to integrate stakeholders and find holistic and balanced solutions.

Keywords: Serious game, biodiversity communication, scientific communication, interdisciplinary research, virtual reality, renewable energy, stakeholder engagement

1 Introduction

When developing future scenarios for the transition to renewable energy, three aspects need to be balanced: economic feasibility, ecologic sustainability, and landscape impact. However, these aspects often conflict with each other – an economically efficient power plant may impair the local ecology and undesirably alter the visual identity of the landscape, leading to citizen resistance. On the other hand, the transition to renewables provides unique opportunities for synergies. Ground-mounted photovoltaic (PV) in particular can satisfy energy demands while also being beneficial towards the local ecology compared to the previous land use, provided a holistic planning and implementation (CUI et al. 2025).

To find such holistic solutions, inter- and transdisciplinary approaches are needed: different disciplines must be able to include their respective data and expertise, linking them to real-world needs and concerns (LAWRENCE 2010). The involvement of stakeholders has proven valuable (BIDWELL 2016), but raises the question of how to integrate and communicate the

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variety of scientific data, and how to include the subjective opinions of the affected people. How can a transdisciplinary consensus be reached based on interdisciplinary data and specific regional knowledge?

Serious games offer a promising solution: they have been shown to be effective in communicating data in understandable ways, fostering engagement, and promoting productive discussions (BOYLE et al. 2016, SCHAUPPENLEHNER et al. 2024). As opposed to traditional games, serious games have a purpose beyond entertainment, such as education or communication; however, they share the common characteristics of games, particularly the use of game mechanics and targets which the players need to reach (ZYDA 2005). To develop such a game logic, a simplified model of the systems linking economic, environmental, and social data in the context of PV planning is needed. In order to also depict the visual landscape effects, the game can be combined with immersive landscape visualization (LOVETT et al. 2015).

In this article, we present a process for integrating various scientific datasets into a serious game definition. This process is conducted as part of an inter- and transdisciplinary research project examining potential conflicts and synergies of ground-mounted PV development on plots currently used for agriculture. The serious game approach aims to involve various interest groups in the development and consolidation of PV scenarios at a regional level. To make their decisions more tangible, an interactive landscape visualization is integrated to include the visual impacts in the discussion. The resulting serious planning game is used in three case study regions in a total of five stakeholder workshops. Actions and statements made at these workshops are recorded anonymously; these outcomes serve to validate the presented approach.

2 Materials and Methods

2.1 Serious Game and Visualization Technology

A serious game and virtual reality landscape visualization toolkit developed in the game engine Godot is used as the basis. The toolkit utilizes GIS data to create 3D landscapes and to define a set of rules, constraints, and opportunities for the game logic. The individual components of the immersive 3D landscape are defined by combining multiple GIS layers into 3D *layer compositions*: for example, a layer composition which renders buildings accesses a vector layer of building polygons and a digital terrain model for placing each building at the correct height. Open governmental data and volunteered geographic information (VGI) are used as a basis for both the visualization and the game logic. The data and rendering components required for depicting a landscape as-is serve as the starting point for this study; the visualization is then extended with components for the specific use-case of PV planning.

In order to discuss ecological impacts or synergies of ground-mounted PV, it is important for different management regimes and layouts to be represented accurately in the visualization. This is realized by making the ground cover and vegetation rendering components react to newly placed PV rows: virtual PV panels can alter the land cover data, replacing the previous vegetation (usually agriculture) with varying soil and plant growth underneath, behind, in front of, and around modules. The effect of this is shown in Figure 1.

Fig. 1: Visualization of different management methods of PV fields: intensive (left, graveled and regularly mowed, distance of 2m between modules), medium (center, mowed and mulched, 4m between modules), and extensive (right, measures taken to promote flowering plants, 6m between modules)

For the game logic, layers are wrapped as *game object collections*, with each GIS feature (point, line, or polygon) in such a layer becoming a *game object*. These game objects can have attributes of different types: they may come directly from a GIS attribute, or they may correspond to the value of a raster layer at their position, or they may even be an aggregate of other attributes based on a given formula. Attributes can be visualized per game object or summed into scores, which may also have a target which the players are suggested to reach.

Rather than using traditional computer inputs, we use the input method described by Schauppenlehner et al. (2024) to allow stakeholders to intuitively and spontaneously interact with the serious game. A map is projected onto a table and toy bricks can interact with this projection. For example, a red brick may depict a PV plant to be placed at that location. The bricks also serve as the input to the user interface, allowing players to make changes to individual PV plants such as changing the distance between rows or the surrounding fencing. Indicators and scores are displayed on this interface as well. As the input method is directly connected to the serious game and landscape visualization, the effects of the participants' actions are visible in real-time.

2.2 Interdisciplinary Game Development

This serious game is developed as part of an inter- and transdisciplinary research project. Specifically, experts in energy economy, biology, and social sciences are part of the interdisciplinary group. In an iterative process, we incorporate and interconnect different thematic data outputs and validate the result based on their expertise and scientific studies. In practice, this iterative process unfolds as follows: experts provide a dataset along with a description of outcomes from their field. Together, we discuss how to best simplify and integrate this data into the serious game. Based on this discussion, a first implementation is built, which is then tested together with the experts. The process is repeated as needed based on their feedback.

Care must be taken to strike a balance between playability and visual fidelity on the one hand, and objectivity and accuracy on the other. For example, a game may elicit a stronger emotional response if biodiversity is visualized in an exaggerated way, while this causes accuracy (and potentially credibility) to suffer (SKULMOWSKI et al. 2022).

2.3 Stakeholder Workshops

The serious game developed as part of this case study is intended to be used to collaboratively plan potential future PV scenarios in stakeholder workshops. To test the efficacy of the tool

in such a workshop, it is applied in a total of five different stakeholder workshops throughout three different regions in Austria. Local stakeholders such as politicians, people involved in energy cooperatives, and interested citizens are invited, with an average of 8 participants per workshop. 3 hours are scheduled for each workshop, about half of which is set aside for the serious PV planning game.

It should be noted that the concrete results of the case study, as well as the specific methodology of stakeholder involvement applied here, are not the primary focus of this article. Rather, the stakeholder workshops serve to assess the impact which the tool has on the workshop, and how it influences discussions and decisions made by the participants.

Verbatim statements made by the participants while playing and discussing the serious game are recorded in a pseudonymized written protocol. In order to ascertain the role which the serious game plays in the discussions and whether it communicates the conflicts and synergies effectively, a thematic analysis is then applied to these protocols. Specifically, the *codebook thematic analysis* according to Braun et al. (2019) is used to iteratively generate and assign themes from the protocols.

3 Results

Two distinct results will be described: the serious game, which combines data from different disciplines into a simplified game logic and visualization, and the evaluation of the stakeholder workshops, which serves to assess whether the serious game was effective.

3.1 Serious Game Definition

In an iterative process described in section 2.2, a serious game logic is defined based on data compiled and processed by experts throughout the project. A flow chart diagram of this game logic is shown in Figure 2.

In the game, participants can place photovoltaic plants and configure the following design parameters for each of them:

1) **Land management**: intensive, moderate, or extensive
2) **Size of PV plant**: 0.5 hectares, 2 hectares, or 8 hectares
3) **Spacing between rows**: 2 meters, 4 meters, or 6 meters
4) **Fencing**: none, hedge, or chain-link fence

In combination with pre-calculated spatial datasets and fixed constants, these parameters serve as the basis for estimating biodiversity impacts and calculating economic outputs.

To calculate the **energy production** of a PV installation in kWh/a, a pre-calculated energy potential dataset (in kWh/kWp) is accessed and multiplied by the number of modules (derived from the size and row spacing of the PV plant) and their power rating. The total cost of a PV installation is a sum of the system costs (depending on the number of PV modules), grid costs (depending on the location), and maintenance costs (depending on the size and management regime); the underlying data for this was provided by partners in the interdisciplinary project team. Dividing this cost by the energy production yields the **cost per kWh**. This

cost is not judged by the game, but presented to participants as-is; it serves as another factor to consider for their subjective, overall evaluation. It should be noted that indirect costs, e. g. lost profits due to reduced agricultural use, are not considered; the cost factor does not provide a holistic economical evaluation, but an estimate of the electricity price.

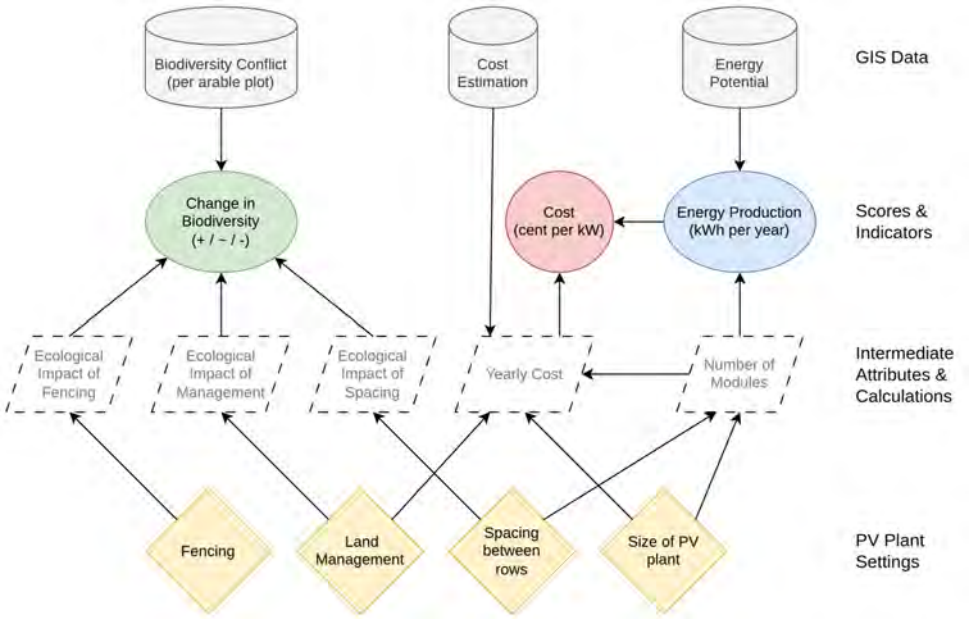

Fig. 2: Flow chart diagram of the serious game logic showing how GIS datasets are connected to attributes and user inputs

Integrating the ecological data to calculate a **change in biodiversity** required multiple iterations. Using the national IACS (INVEKOS) dataset (AMA 2025), each agricultural plot within the case study area is rated with an ecological potential for conflict (EPFC) based on its current condition and cultivation (low, medium or high EPFC). A low EPFC means that biodiversity is currently scarce (e. g. intensively cultivated crops), while a high EPFC value indicates that the existing land use creates high ecological value (e. g. extensive meadows) and changes in land use are likely to adversely affect biodiversity. For further detail on the methodology behind this classification which was devised as part of this project and utilized for the serious game, we refer to Hainz-Renetzeder et al. (2025).

Each decision made by the participants regarding the design and management of a PV system is assigned an environmental impact based on the EPFC of the plot in which it was placed. These impacts are defined together with biologists based on field surveys in which they compared photovoltaic sites with reference plots. The sum of the ecological impacts of one PV system is an integer value. Because of the difficulty of quantifying ecologic impact, only the sign of this value is communicated in the game as a general trend: Negative values indicate a decline in biodiversity, positive values correspond to a potential increase in biodiversity, and zero implies that biodiversity will remain largely unchanged. Generally, installing PV in

locations with a high EPFC will always lead to negative biodiversity impacts, while areas with a low EPFC generally see an increase in biodiversity unless the PV installation is configured to be highly dense and intensively managed. The rating scheme is shown in Table 1. Of course, these are estimations which serve primarily to initiate discussions among participants on the trade-offs to be made, not to provide definitive assessments of individual plots.

Table 1: Impact of different ground-mounted PV configurations on the biodiversity score in the serious game based on the ecological potential for conflict (EPFC) of the previous land use

EPFC		Low	Medium	High
Row Distance	6m	+2	+2	-1
	4m	+1	0	-2
	2m	0	-2	-3
Fencing	Chain-link	-1	-1	-1
	Hedge	+1	+1	+1
	None	0	0	0
Management	Extensive	+2	+2	-1
	Moderate	+1	0	-2
	Intensive	-1	-2	-3

In addition to displaying these indicators within each PV installation, two global game targets are added to the game. One is energy production: players can see how much their currently planned PV installations contribute to the national energy targets (scaled to each workshop region). The second target is the assessment of the effects on biodiversity. Because this cannot meaningfully be communicated as a numeric value, it is displayed as a deviation from the status quo: participants can see if, in total, their activities have a potential to improve or worsen the biodiversity within the workshop region. These two scores are displayed individually and not summed into a total score, since the weighting should be up to the participants.

3.2 Visualization

Like the biodiversity indicator, the definitions and visual representations of different management regimes are developed iteratively together with experts in the field. Based on field surveys within existing PV plants, typical distinct management regimes are identified, and corresponding ground and plant textures are assigned based on the reference PV installations to match their visual appearance as closely as possible.

Players can choose between three management regimes: *intensive*, characterized by short, frequently mowed grass; *medium*, dominated by species-poor grassland due to mulching; and *extensive*, where specific measures are taken to promote a diversity of different (flowering) plants. Four ground cover types are defined for each management regime: vegetation directly underneath each module, in front of a row of modules, behind a row of modules, and in the remaining area. The strips before and behind modules have a width of 1 meter. Figure 3 illustrates the visualization of these areas for each management regime and features some of the textures used in the visualization.

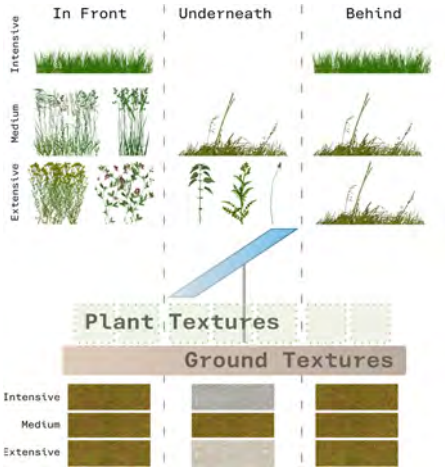

Fig. 3:
Schematic depiction showing how vegetation is configured and visualized around PV modules. The textures shown are examples of textures used in the 3D visualization; they are selected based on location and management regime.

3.3 Stakeholder Workshop Evaluation

Two tags are assigned to each entry in the written workshop protocols. The first signifies the **scope** in which the discussion was taking place:

- *Within:* Discussion in direct reference to the serious game or visualization
- *Beyond:* Discussion of siting-related topics beyond the direct scope of the game
- *About:* Discussion of the methods (the serious game, the visualization, or the underlying data) at a meta-level

The second tag specifies the **content** of the discussion. Some directly correlate to themes brought up by the game, specifically *Energy*, *Ecology*, *Visual*, and *Economy*. Others refer to new themes brought up by participants; these include *Legal*, *Other Renewable Energy*, and *Method* (statements or questions about the game, visualization, or data).

The *Within* and *Beyond* tags were approximately equally common (41% and 39% respectively), suggesting that the tool facilitated discussion of the content being shown while also encouraging the discussion of new themes. The *About* tag was half as common (20%), indicating that meta-level discussions did not dominate over other topics.

Among discussions *within* the game, the *visual* theme, i.e. participants expressing their opinion on the visualized PV installations, was most common (43%). *Ecology* and *Energy* were discussed at 24% and 20% respectively, suggesting a relatively balanced discussion of ecological sustainability and energy-efficiency. The remaining 13% are tagged with *Method*. Notably, the *Economy* tag never occurred at the *Within* scope.

In discussions *beyond* the game, visual aspects account for just 9%, indicating that participants were able to sufficiently discuss this aspect *within* the visualization. *Ecology* and *Energy* account for 20% and 15% respectively; these statements usually added specific local knowledge which was not present in the game data. *Economy* also accounted for 15% of statements *beyond* the game. Similarly, discussions about *legal* aspects, which were not cov-

ered by the game at all (except implicitly by the inclusion of legal boundaries between agricultural plots), account for 15% in this scope. Other types of renewable energy were also brought up in most workshops.

Discussions *about* the game largely centered around the *method* with 46%. This includes e. g. questions about the usage of the tool and remarks about the feasibility of the plans as simulated in the game. The remaining topics in the *About* scope are spread relatively equal, usually questions about the underlying data or statements about potential inaccuracies. This scope was usually most prevalent in the first halves of workshops, while the *within* scope was more frequent in the second halves.

Comparing the protocols between individual workshops reveals that the focus varied significantly. In some workshops, the *visual* impact played a central role, making participants rely primarily on the landscape visualization. In others, the discussion centered more on the practical aspects of *economy* and *energy*, although as noted above, while the discussions of *energy* did often center around the data provided by the game, discussions of *economical* aspects did not take the game into account, often occurring at the intersection with political topics (funding) rather than the purely techno-economical calculation.

Although there were significant differences between the workshops, *energy* and *ecology* as presented *within* the game were a topic in all of them, and in each workshop, participants actively attempted to reach the national energy target while paying attention to causing no negative total impact on biodiversity. This suggests that the global scores effectively influenced the discussion, while being open enough to facilitate sufficient discussion of other aspects *beyond* the serious game.

4 Discussion

In the context of an inter- and transdisciplinary research project, a comprehensive serious game for PV siting at the regional level was developed, taking economy, ecology, and landscape into account. Complex data and interrelations were translated into a comprehensible game logic. The accompanying immersive landscape visualization shows the specific parameters of the PV installations and how they fit into the surrounding landscape.

The iterative integration of the interdisciplinary data into the serious game also provided a unique opportunity for the other experts to reflect on their data output and simplify and generalize it, while still being comfortable with the accuracy. This process of gamifying data outputs may aid not only the external presentation of the results, but also the internal cooperation and communication in interdisciplinary projects. A future article will analyze the interdisciplinary cooperation within this scientific project in its entirety.

The workshops showed that the game provided a useful basis for discussion and collaboration. In particular, the national energy targets and the total biodiversity score influenced the participants' choices in all workshops. In some cases, the visualization was a crucial aspect and allowed participants to effectively factor the subjective visual landscape impact into their plan. On the other hand, participants paid no attention to the economic score expressed in cent per kWh, instead discussing other economic aspects such as funding. It is possible that this difference was partly caused by the lack of a total target for this aspect. However, it should be noted that participants did still discuss this point and factor the discussion into their

plan, suggesting that it was important for the serious game not to be overly restrictive, providing a basis for discussion but not insisting on it.

Our method, from technical implementation to practical usage, could be applied in a variety of other landscape planning and development processes, particularly those involving similar conflicts of interest. Alongside other forms of renewable energy, the joint and holistic planning of nature-based solutions using a similar method could be a promising area for future studies. It may also be interesting to transfer these results to other fields and even back to traditional video games: we would encourage game developers, particularly of strategy games, to consider incorporating a realistic ecological component similar to the game logic developed in this study.

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Treespotting AR (TS^{AR}): Re-Enchanting Minimal Phygital Ecologies

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Abstract: In times of digital abundance, Treespotting AR (TS^{AR}) challenges the hyperrealism of technocratic digital twins and XR applications. Learning from Cesare Leonardi and Franca Stagi's experimental graphics deployed in their seminal work "The Architecture of Trees", TS^{AR} translates their reductionist logic into a monochromatic point cloud installation. By minimizing data to maximize phenomenological engagement, the project explores new forms of mediated encounters with urban nature. Field-tested by 430 participants, the installation demonstrates how abstract visualization can foster reflection about the multiple formalizations of AR while investigating speculative and participative design, proposing a shift from managerial data to embodied, phygital encounters.

Keywords: Augmented reality (AR), point cloud, phenomenology, digital twin, landscape representation

1 Introduction: The Challenge of Digital Abundance

We currently confront a paradigm shift where new technologies as LiDAR, photogrammetry, and neural rendering, dense point clouds, and Extended Reality (XR) promise unprecedented fidelity and enhanced interaction. However, this "digital abundance" (HOVESTADT et al. 2017) introduces a new epistemological challenge (HELBING & ARGOTA SÁNCHEZ-VAQUERIZO 2023). It makes us question whether ultra-detailed geometry and virtually endless data layers clarify the integration of nature into design, or if they obscure it through "technocratic solutionism".

In this context, we revisit the legacy of Cesare Leonardi and Franca Stagi's "The Architecture of Trees" (1982) (LEONARDI & STAGI 1982) to propose a critical framework for digital representation. We ask: *how can their representational logic, i. e. balancing precision with abstraction, guide the processing of point clouds into meaningful spatial design information in AR, thereby countering the limitations of technocratic digital twins?*

Hence, we present Treespotting AR (TS^{AR}), an AR installation that reimagines Leonardi's methodology through contemporary 3D scanning and visualization techniques, challenging conventional representational modes in landscape design. By navigating this specific case study, the project explores the friction between the endless possibilities of digital representation and the grounded contingency of physical reality. Unlike traditional approaches, TS^{AR} is not a drawing, a model, or a photograph; it is a curated sampling of a living entity. TS^{AR} operates as an ontological threshold where traditional categories such as object, space, surface, or boundary, lose rigidity and are renegotiated through phenomenological experience. It is designed to be partial but situated, relational, and performative, existing only within an active relation with the viewer.

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Crucially, a landscape or urban design project, as any design project, is, by definition, a virtual project. The relative indetermination of a design proposal is one of its fundamental features. It is the indetermination of the representation of architectural projects what allows it to "speak", and "be a matrix of possible narratives regarding the kind of built reality it anticipates" (PICON 2004). "Like cyberspace, a designed landscape is always at bottom a fiction, a contrivance – yet its hold on our imagination will derive, paradoxically, from the actual materiality of its invented sceneries" (HUNT 2004). Even though a designed landscape is a 'fiction', its imaginative power stems, paradoxically, from the physical materiality of its invented spaces. Accepting the fictional character of something so "accurate" as a point cloud allows designers to honestly engage with the possibilities it encapsulates.

Etymologically, "data" refers to things that have been given, whereas "information" implies data having been put into form. TS^{AR} enacts this distinction by putting a raw scan into form. It questions the roles of fidelity, accuracy, and completeness, serving not as a final representation, but as the generation of a world in which design thinking can take place.

2 Related Work and Theoretical Framework

2.1 The Legacy of Cesare Leonardi

To answer the question of how Leonardi and Stagi would work today, one must look beyond the aesthetic of Leonardi and Stagi's drawings to the logic that constructed them. Leonardi and Stagi did not merely illustrate botany. Instead, they proposed a systematic abstraction that distilled the shape of trees, seasonal change, and shadow into scalable diagrams relevant for design, and turning trees into relevant architectural actors rather than mere ornaments (Fig. 1).

However, translating this conceptual clarity into the current digital abundance without falling into digital formalism requires a rigorous theoretical framework. Therefore, the use of the point cloud presented in TS^{AR} is not conceived as raw data, but as a form of "cognitive art" (TUFTE 1990).

Individualization over Typology

Leonardi and Stagi refused to draw a generic tree, insisting instead on the specific one they encountered. Their drawings captured not only form but also posture, growth history, asymmetry, and the species' topological branch logic. Each drawing was not a type, but a singular entity, turning drawing into an act of individuation. TS^{AR} adopts this approach. Where some might view the irregularities of a point cloud as noise, here it is seen as the necessary texture of singularity. This aligns with the argument that digital urbanism must move beyond the illusion of "precise data" to embrace the uncertainty of urban, human reality (DELSO GUTIÉRREZ & ARGOTA SÁNCHEZ-VAQUERIZO 2023, CALDARELLI et al. 2023). TS^{AR} uses the point cloud to inhabit a terrain between precision and abstraction, avoiding geometric homogenization common in standard CAD representation of nature, where organic complexity is often standardized into static blocks (M'CLOSKEY & VAN DER SYS 2017).

Temporal Thickness and the Defense of Complexity

Leonardi and Stagi's work was never a frozen moment, but a relationship of trees over time. This resonates with what Jeremy Till describes as "thick time" understood as a rejection of the instantaneous snapshot in favor of an accumulated temporal reality (TILL 2000). The drawings of "The Architecture of Trees" required attentive and prolonged observation to see time, growth, and particularities. To replicate this depth in a digital medium, it is needed to embrace visual complexity. TS^{AR} leverages the principle that "clutter and confusion are failures of design, not attributes of information" (TUFTE 1990). Therefore, the high density of the point cloud is retained not to confuse, but to allow the viewer to select, edit, single out, and structure the information. This density enables a mediated encounter where the viewer must actively navigate the multi-scalar readings of the tree, just as they would with Leonardi and Stagi's intricate linework.

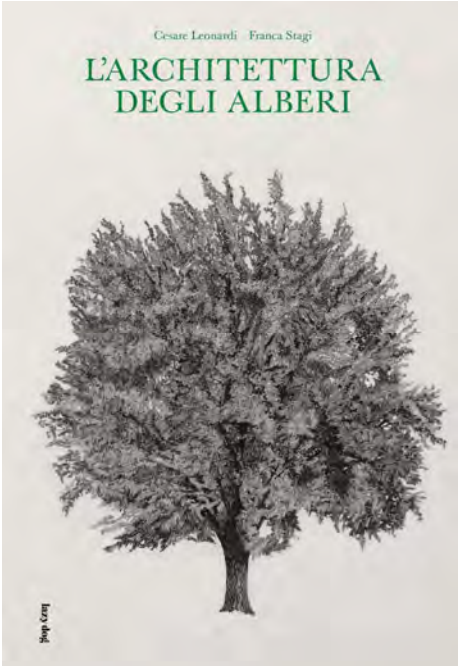

Fig. 1:
Cover of the "L'architettura degli alberi" ("The Architecture of Trees") with one of the drawn trees (LEONARDI & STAGI 1982)

From Documentation to Speculation

Leonardi's drawings inhabit a blurred terrain between documentation (i. e. representation) and proposal (i. e. speculative proposal). They became a space of reflection for practice. Following this, TS^{AR} is proposed not only as a documentation tool, but as a framework for speculation. Rather than considering the point cloud as a managerial asset, TS^{AR} aims at the "phygital" (physical + digital) medium (BAZZANELLA et al. 2014). This approach is simultaneously quiet and rich for perceptual re-examination, and perhaps, re-enchantment (DUNNE 2005). Consequently, it serves as a catalyst for the viewer's imagination, potentially serving as the first entry in a new virtual catalogue, which can be envisaged as a contemporary digital counterpart to Leonardi and Stagi seminal work.

2.2 Context: Perceptual vs Managerial Digital Twins

While Leonardi provides the methodological foundation, it is necessary to situate TS^{AR} within the current technological landscape. Recent discourse in Digital Landscape Architecture has mainly framed digital twins as managerial instruments. Urban-scale twins support climate resilience modeling (ZHU & JIN 2025, SALLIOU et al. 2025), biodiversity monitoring (WESTERLAKEN 2024), simulation (CHEN et al. 2024), and real-time environmental sensing. While these systems provide valuable support for green infrastructure management, their representation of trees is often simplified to facilitate calculation (GROMKE & RUCK 2007).

Simultaneously, research on Human-centric, community and participatory design has explored AR as tools for spatial engagement (AHMADI OLOONABADI & BARAN 2023). However, many applications remain constrained to consultation processes, simply overlaying technical data without enhancing deeper ecological fine-tuning. This also resonates with critics pointing out that digital representation does not mean "groundtruthing", as mediation, which digital representation is, always shapes perception (REKITTKE et al. 2021).

TS^{AR} sits at this intersection, leveraging Computation and Digital Technologies to advance perceptual digital twins prioritizing insight over data exploitation. This approach aligns with emerging critiques on "digital solutionism" (MOROZOV 2013). Therefore, TS^{AR} advocates for a relational perception: using digital tools to recalibrate, attune, human awareness of ecological presence.

3 Methodology: Workflow and Implementation

The methodology translates Leonardi's logic of selective observation into a reproducible digital workflow, integrating current 3D scanning technologies and XR. The process follows three distinct phases: Data Acquisition (Scanning), Processing (Abstracting), and Deployment (Augmenting).

3.1 Data Acquisition: Scanning

The case study focuses on a mature *Platanus* × *acerifolia* located at the Karlsruhe Institute of Technology (49°00'38.3"N 8°24'40.2"E), selected for its structural integrity and lack of pruning. The scan yields a raw point cloud of roughly 17 million points, preserving geometric detail while retaining sensor's limitations such as occlusions by dense foliage and branches or noise in shadowed or reflecting areas. Rather than cleaning the data to produce a simplified mesh, these artifacts are preserved as the inherent texture of the digital scan (Fig. 2).

3.2 Processing Strategy: Abstraction

Instead of reconstructing the missing geometry with synthetic geometry (LEE et al. 2025, YAO & FRICKER 2024) we preserve the point cloud with minimum processing. To avoid the technocratic solutionism of hyper-realistic rendering, the visualization strategy follows a strict reductionist protocol. Where Leonardi reduced a tree's complex variables to two spatial dimensions (x, y) and a binary (i. e., monochrome) ink value, TS^{AR} operates in three dimensions (x, y, z) but reduces the color variable (R, G, B) to a uniform black (0, 0, 0). This removes the reliance on photorealism. The resulting visual output relies entirely on granulometry, i. e. the density of points per cubic meter, to convey volume and opacity. This ensures the digital twin functions as a structural diagram rather than a cosmetic replica.

Fig. 2: Elevation of the scanned digital surrogate of the *Platanus* × *acerifolia* located at the Karlsruhe Institute of Technology (49°00’38.3”N 8°24’40.2”E) (Image Credit: the authors)

3.3 Deployment and User Interface (UI): Augmenting

To address the need for accessibility without specialized hardware (e. g., Virtual Reality headsets), the point cloud was optimized for WebAR (Web-based Augmented Reality) using the AR Code platform. The file was downsampled to <10MB using an octree compression structure to ensure low-latency loading on standard smartphones (iOS and Android) and accessibility via standard web browser.

Field Setup: The experience was anchored to a fixed geographic position at Festplatz in Karlsruhe (49°00’11.3”N 8°24’09.7”E) during the *Media art is here* festival. Through the festival 430 participants scanned the QR code and actively interacted and navigated the 1:1 scale digital entity (Fig. 3) in situ.

User Experience (UX): Addressing the interface design, TS^{AR} adopts a minimalistic interface approach. Upon scanning the QR code, the user sees only the camera feed and the superimposed point cloud. There are no menus, botanical labels, or data overlays. This absence of interface clutter is a methodological choice to force a direct, phenomenological encounter. The user’s role shifts from reading data to navigating space, i. e. walking around and through the point cloud to comprehend its structure (Fig. 4).

Fig. 3: One person using a cellphone at Festplatz, Karlsruhe to visualize the AR model of the *Platanus* × *acerifolia* during the *Media art is here* festival (Image Credit: Felix Grünschloß)

Fig. 4: AR navigation around the model of the *Platanus* × *acerifolia* during the *Media art is here* festival at Festplatz, Karlsruhe, as seen in a cellphone (Image Credit: the authors)

4 Discussion: Progress and Uniqueness

Merging well-known point cloud technology with the methodological principles of "The Architecture of Trees" provides a unique framework to explore the phenomenology of TS^{AR} and its implementation in landscape architecture practice.

4.1 TS^{AR} as a Critique to Representation

This project extends, and reinterpret, Leonardi's paper-based static 2D analytical drawings into a 4D phygital experience (3D space + time/interaction). Unlike a drawing, the point

cloud reveals volumetric complexity, parallax, and spatial immersion, which allows users to inhabit the tree's form rather than simply viewing it. This shift moves beyond documentation toward embodied perception, enabling human cognition and interaction: representation becomes experience. As Leonardi's drawings, TS^{AR} requires attentive and prolonged observation, there is more to see than forms: time, growth, exception and particularities are revealed to the exhaustive viewer.

The project uniqueness lies in its critical position towards digital aesthetics. It avoids hyperreal rendering, or exuberant formalism of common consumer AR applications. Instead, it embraces the point cloud's inherent abstraction, becoming a curated sampling of a living entity. This results into a simultaneous feeling of metric accuracy (and so, realism), and artificial fragmentation, a tension that highlights the mediated nature of all representation, challenging traditional landscape architecture documentation methods.

4.2 TS^{AR} as a Mediated Encounter

Digital technologies promise inexhaustible detail. Yet abundance can be anaesthetic. The precision of millions of points may overwhelm the perceptual economy that makes drawing intelligible. While Leonardi's minimal line encoded essential proportions; the point cloud risks dissolving meaning in numerical excess. TS^{AR} therefore experiments with reduction: decimated datasets, single point size, and false-monocolor generate alternative "aesthetic regimes" (RANCIÈRE 2000) of digital botany. These acts of restraint recall the selective framing of analogue representation and resist the contemporary fetish for hyperreal visualization that dominates architectural imagery.

This position aligns with critiques of hyper-technological aesthetics and techno-spectacle in design culture (DEBORD 1967). By enforcing aesthetic scarcity within digital abundance, the project resists the uncritical valorization of photorealistic rendering and excessive computational complexity. Such visual regimes often mask sensory hyper-saturation (BAUDRILLARD 1981), capturing attention and eroding contemplation (HAN 2010). In contrast, the project privileges ambiguity, allowing perception rather than data to complete form, becoming an ontological threshold where traditional categories (object, space, surface, boundary) lose rigidity and become renegotiated in phenomenological experience. This mediation is made evident, visible and adjustable, affecting the three stages of understanding (KIRK 2016): perceiving, interpreting and comprehending. The impact on the last phase implies that the digital twin becomes a medium and a territory for design speculation.

4.3 TS^{AR} as a Design Enabler

The *Media art is here* festival participants are not designers or people with particularly strong digital competences, just Karlsruhe citizens and visitors, interested in interacting with the proposal. User feedback was informally collected during several moments of the festival, highlighting the application's immediate accessibility and ease of use, as well as the intuitive legibility of the augmented tree representation. The chosen graphic abstraction was perceived as particularly effective in leaving interpretative space, thereby enabling users to imagine alternative spatial configurations involving the implanted tree.

This project is not a final representation, but the generation of a world in which design thinking takes place. De Landa distinguishes between the actual (i. e. a property, like a tree's current state) and the virtual (i. e. its capacities and tendencies, what it can do). The virtual

is “fully real” as a structure of possibilities (DeLANDA 2015). In our case, the actual is the specific, imperfect point cloud dataset that was captured. The virtual is the structure of possibilities that this data implies. The gaps and variations in the point cloud don’t just represent “missing data”; they represent the tree’s capacity to grow, change, sway in the wind, lose leaves, and be seen from different angles. They are a digital record of the tree’s degrees of freedom.

A perfect model would kill the virtual; it presents the tree as a finished, actualized object. An imperfect point cloud, however, preserves the virtual. It is a representation that acknowledges what the tree is but also hints at everything it could become. It is a “structure of a possibility space” for the tree’s future growth and interaction.

This approach questions also authenticity, as it is a digital surrogate that omits roots, soil, scent, sound, and even biological and energy flows. As cities increasingly adopt twins for planning, it is important to pinpoint that fidelity is not the same as truth. A scan may capture geometry, but it cannot convey ecological relationships without deliberate curation.

TS^{AR} is not only valuable for urban nature planners but also reframes participation through relational design. While AR, and more broadly XR, are often used to increase citizens’ engagement and participation on design proposals (AHMADI OLOONABADI & BARAN 2023), we propose here that meaningful participation starts with perception. Before people can co-design with digital tools, they must first develop a shared, affective relationship. This positions XR not as a mere consultation interface, but as pedagogical medium and ecological literacy connected to more-than-human care.

5 Conclusion

TS^{AR} continues Leonardi’s legacy not by replicating his methods, but by translating his core question of how we can see trees as integral to architecture into the digital present. It speculates that the future of digital representation in landscape architecture depends not only on ever- higher fidelity, but on thoughtful curated mediation. It means choosing what to show, what to omit, and how to frame the encounter.

By translating Leonardi and Stagi’s reductionist graphics into a spatial experience, TS^{AR} shows that a minimalistic AR installation stripping away hyper-realistic textures and visualization from digital abundance paradoxically can amplify phenomenological engagement with urban nature. Removing explicit UI elements and the direct immersive overlay of the sole point cloud as a primary aesthetic invites the viewer to actively navigate through a physical encounter shifting the participant’s focus from the device to the organism.

Critically, TS^{AR} positions XR as a counter-narrative to the prevailing logic of Urban Digital Twins, where the latter reduce vegetation to computable entities for simulation efficiency. Hence, TSAR shifts the role of the digital model from an instrument of quantification to an instrument of qualification, that privileges organic singularity over algorithmic precision.

Ultimately, TS^{AR} reframes the landscape architect’s role from designing static planting schemes to curating phygital encounters, using the point cloud not as a data product but as a pedagogical medium for ecological literacy and reflection. Therefore, it is possible to think about digital tools that can do more than optimize or simulate: they can re-enchant, in the sense of cognitive and affective engagement, without overexciting and calling for attention.

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Photorealistic Visualization of Quarry Regeneration Using UAV Imagery and Game-Engine Rendering

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Abstract: The presented case study examines the visualization of a multi-stage quarry regeneration project. We employed georeferenced GIS data, UAV imagery, Unreal Engine, and Blender motion tracking to produce a continuous video simulation of the quarry's future state. By using motion tracking in Blender, we extracted reference points to align real-world imagery with the digital scene. The resulting camera path was exported to Unreal Engine for high-fidelity visualization. This workflow provides a robust method for dynamic camera positioning, ensuring seamless alignment between the 3D models and the actual terrain across the video sequence.

Keywords: Quarry regeneration, motion tracking, Unreal Engine, landscape visualization, UAV, georeferenced workflow

1 Introduction

Visualization has long been a central tool in landscape architecture (LANGE 2011), enabling designers to communicate spatial ideas planning scenarios (SHEPPARD et al. 2011), raise public engagement as well as anticipate public reaction to proposed changes in landscape scene (SULLIVAN et al. 2021a). Visualizations hold a special position, particularly in landscape architecture. In addition to creating visually compelling images, visualizations must provide insight into changes in the landscape across relevant habitats and maintain sufficient representational validity.

While visualizations of gardens and urban spaces are well-established disciplines, the situation is more demanding in the case of the open landscape, where landscape features play a significant role.

When depicting projects in the open landscape, three fundamental technological approaches can be used, each offering a different balance of precision, aesthetics, and flexibility:

1. Photomontage (Static Simulation into Photography) (PALMER & SULLIVAN 2020, SULLIVAN et al. 2021b): This method offers the highest degree of photorealism by using actual images of the site. Its primary disadvantage is its static nature and inefficiency regarding design changes – for every new perspective or project variant, the entire simulation process (model placement, lighting, and shadow settings) must be repeated.
2. Digital Scene Modeling (BITTNER et al. 2024, HELLER 2024): Creating a complete digital twin of the landscape allows for unlimited viewpoints, video production, and VR experiences. This approach can be extended by a 4D dimension (simulating vegetation growth over time and seasonal changes) and procedural generation, which uses algorithms to automatically populate vast areas with biologically accurate vegetation.
3. Integration into Scanned Environments (Point Clouds and Hybrid Models (FISCHER et al. 2020) or Neural Radiance Fields – NeRF (SCHOB & REKITTKE 2023). This method

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utilizes data from laser scanning or photogrammetry for maximum geometric precision. While traditional point clouds often suffer from a loss of photorealism due to image fragmentation, modern methods such as 3D Gaussian Splatting (KERBL et al. 2023) eliminate this shortcoming, combining scan precision with photographic visual quality in a fluid 3D space.

For the case study, we used a 'copy-paste' approach, where only the specific part of the project subject to change was modeled and subsequently merged with UAV video imagery. The novelty of the approach lies in adaptation of VFX technique matchmoving. This cinematic technique allows the insertion of computer graphics into live-action footage with correct position, scale, orientation, and motion relative to the objects in the shot (DOBBERT 2012). By leveraging automatic matchmoving to register the 3D elements within the video sequence, the manual workload was significantly reduced. This workflow effectively combines the procedural creation of modified landscape features with real-world video capture. Ultimately, it demonstrates the potential of integrating UAV-based documentation with game-engine rendering to produce photorealistic and spatially accurate visualizations for environmental assessment and landscape design communication.

2 Method

The case study focuses on the initial phase of a quarry with a projected 30-year operational lifespan, encompassing two stages of mineral extraction and parallel site renaturation. Given the project's scale, visualization was integrated directly into the planning process. To address the quarry's specific location, two distinct scales of observation were utilized: UAV-captured imagery to establish the broader landscape context and eye-level observer points to provide realistic, ground-level perspectives of the internal details (the eye-level observer from distant observer point was not applicable).

The presented visualization workflow can be distinguished into four processing steps:

1) Data acquisition and preparation of basic digital models
2) Reconstruction of the camera position and movement
3) Scene detailing and rendering
4) Postproduction

The visualization was based on data provided by the mining company, encompassing all stages of quarry development and its subsequent restoration phases. For the current state, standard georeferenced layers – including an orthomosaic and a Digital Elevation Model (DEM) derived from a LiDAR survey – were utilized.

For scene preparation and further detailing in Unreal Engine (UE) 5.5 (EPIC GAMES 2024), several data types were incorporated, including the UE Landscape component, static meshes, and Nanite Foliage (EPIC GAMES 2025), as well as UE Levels for organizing multiple project stages.

The Landscape component was used to import three GeoTIFF-based terrain models, each representing a different stage of quarry development. GeoTIFF-based terrain models were based on the dataset by the State provider in spatial resolution 5 m ground sample distance (GSD) with a mean square error (MSE) of 0.13 m for forest areas (BĚLKA et al. 2025). Unlike

static meshes, the Landscape system enables texture painting using landscape materials and allows for terrain refinements which made it more suitable for this application.

The second data type: Static Mesh, supports only basic transformations (move, rotate, scale). In this case, static meshes were used primarily as assets for detailed views.

The orthomosaic was applied as a semi-transparent decal projected onto scene surfaces, adding surface detail without modifying the landscape material or mesh. As the project was visualized in stages, changes in vegetation size were also represented. Using Unreal Engine Levels enabled the creation of multiple project stages while maintaining a consistent surrounding environment across all stages.

The second processing step involves motion tracking to reconstruct camera position. For this purpose, the Blender software (BLENDER ONLINE COMMUNITY 2024) was used, as it provides a built-in motion tracking utility capable of automatically detecting and tracking features in video clips (Fig. 1).

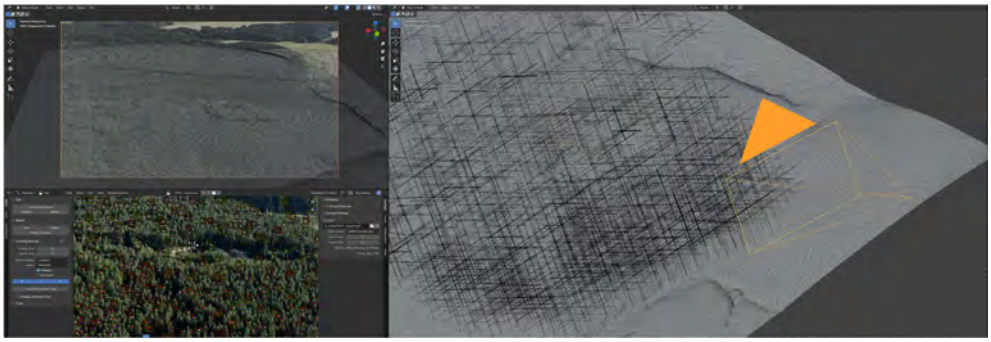

Fig. 1: Camera alignment in Blender: camera view with the video clip and 3D model for visual alignment control (upper left), tracking view with detected feature points (bottom left), and 3D viewport used for the alignment process (right) (Screenshot from Blender)

Selected video clips from UAV were imported into Blender, where an automatic feature detection process was applied. The camera solve error for the footage was 0.68 px for a 40 s rotation around the area and 0.58 px for a 100 s straight overflight. The alignment procedure began by defining an initial set of reference points to approximate the camera's position within the 3D scene. The camera was first aligned using a distinct, clearly recognizable feature in the footage which was identified and matched to its corresponding reference point on the mesh within Blender.

Subsequently, a second feature was selected, and the camera scale and rotation were refined to ensure both features aligned accurately while maintaining the position of the first reference point. To validate the alignment's accuracy, each time at least one additional reference point was examined, and minor adjustments to the camera parameters were made as necessary. The deviation of the control points is hard to measure. Points used for the alignment are within lower tens of centimetres, because were selected to be easily detectable. Outside of the area the deviation is within meters or tens of meters, with decreasing accuracy with longer distance from the camera.

The further detailing involving painting landscape materials, aligning decals, and placing vegetation and finally rendering of the landscape model was processed in Unreal Engine (Fig. 2) using the aligned cameras, exported from Blender.

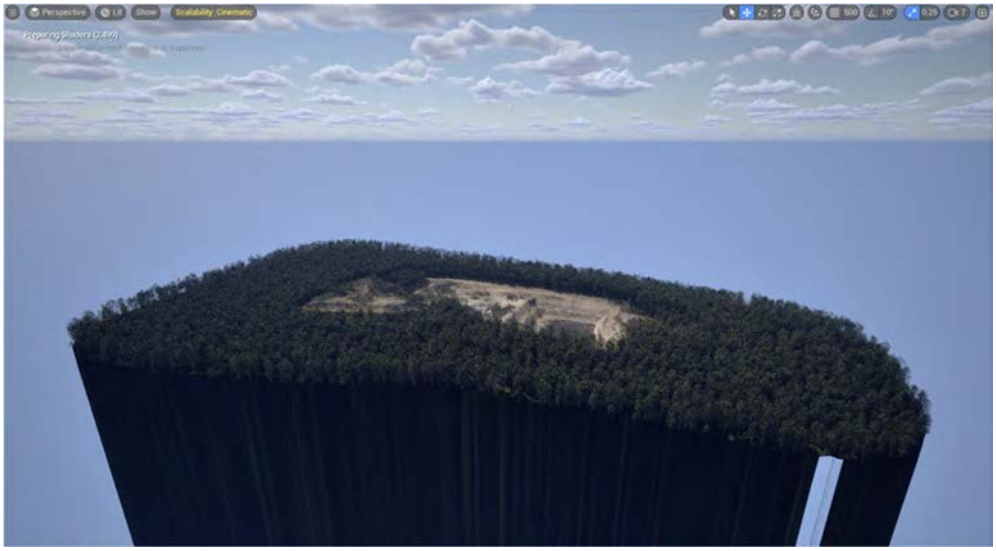

Fig. 2: Spatial scope of the modelled area in Unreal Engine. Representing the entirety of the landscape necessitates a larger-scale 3D model to maintain contextual accuracy (Screenshot from Unreal Engine).

The rendered scene from Unreal Engine (with a transparent background) was then post-processed in DaVinci Resolve to compare the rendered output with the original recorded footage. The UAV footage served as the background layer, while the rendered scene was overlaid on top.

3 Output

The workflow integrates 3D models with real-world footage by transitioning from manual camera alignment to an automated motion-tracking process, facilitating photorealistic simulations within video sequences. This approach provides a realistic depiction of the surrounding landscape while eliminating the need to model the entire environment. For distant perspectives, it is sufficient to render only the core project area within Unreal Engine, incorporating just a narrow buffer zone to ensure visual continuity with the landscape (compare Fig. 2 and Fig. 3).

Fig. 3: Combination of UAV footage and Unreal Engine render of the final stage of the project (Screenshot from the video)

Fig. 4: Final level of detail rendered from Unreal Engine

3.1 Time and Hardware Requirements and Workflow Efficiency

Once the workflow was established and appropriate video footage was selected, the complete motion tracking and camera setup process required approximately 2-3 hours per clip. Work within Unreal Engine required an additional 50 hours, covering the import of 3D models, creation of all three project stages, vegetation detailing, and the setup of individual camera views.

Preparation of supporting datasets in GIS and 3D modeling in Blender accounted for approximately 15 hours, while DaVinci Resolve editing – comprising video alignment, color correction, sequencing, and voiceover synchronization – required about 30 hours (Fig. 5). These estimates demonstrate that while the initial setup phase is relatively demanding, the overall workflow becomes substantially more efficient once procedures and visual material are clearly defined.

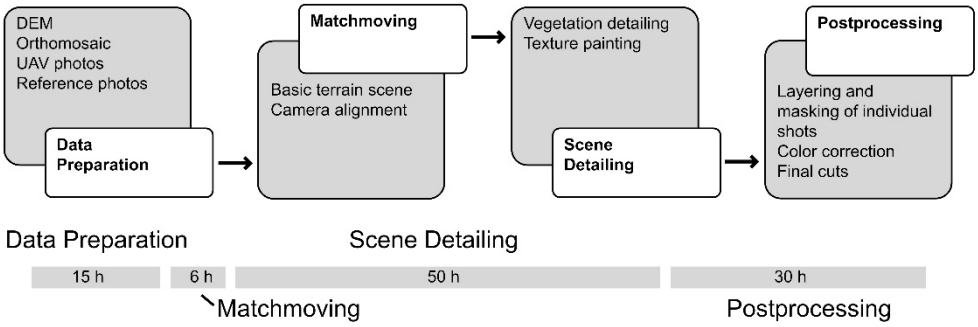

Fig. 5: Diagram showing four phases of workflow and time (hours) requirements for each phase

The workflow was carried out using two separate hardware configurations optimized for different stages of the process. The Blender modeling and DaVinci Resolve post-production tasks were performed on a MacBook Pro with an M4 processor and 48 GB of unified memory, providing sufficient performance for 3D modeling, video editing, and color correction. In contrast, the Unreal Engine visualization and rendering tasks required a more powerful desktop setup, utilizing an AMD Ryzen 7 processor, a NVIDIA GeForce RTX 3090 GPU, and 64 GB of RAM to ensure smooth real-time rendering and efficient handling of complex 3D scenes.

4 Discussion

Developing this workflow revealed several technical challenges that directly impacted the precision of our results. Aligning a scene can be particularly difficult in areas with dense vegetation, such as forests. The process relies on identifiable terrain features that must be visible both in the UAV footage and accurately positioned in the 3D scene (including elevation). At least three reliable reference points were required for successful alignment.

The camera distance and angle affect the precision significantly. If the UAV camera is positioned too far or too high above the target area, the precision of both motion tracking and scene alignment decreases significantly.

Vegetation and occlusion in post-production present a significant limitation for compositing. Dense or tall foreground vegetation, particularly in low-angle UAV shots, can obscure large portions of the landscape behind it. When such vegetation is not part of the proposed future scenario and must be removed, the occluded background cannot be reliably reconstructed due to the lack of visual data. As a result, shots with substantial foreground vegetation occlu-

sion cannot be effectively used for visualization, as clean removal would require information about the hidden landscape that is not available.

Color unification: Achieving consistent color tones between UAV footage and Unreal Engine (UE) renders is time-consuming. It requires careful color correction and fine-tuning of UE render settings to ensure visual coherence.

Foreground masking and tracking: When the UE model occupies the central area of the scene, but foreground elements are required, it can be challenging to create and track masks accurately, so they move naturally with the camera. Environments with denser vegetation may be more forgiving due to their less clearly defined boundaries, which can help conceal minor masking inaccuracies; however, further evaluation is needed to determine which type of landscape is most suitable and technically feasible for this workflow.

5 Conclusion

By preserving camera movement, perspective, and spatial continuity derived directly from UAV video footage, the proposed workflow addresses a gap between static photomontage techniques and fully synthetic digital scene modeling. The resulting visualizations situate proposed landscape transformations within their recorded real-world context, improving the interpretability of spatial relationships. This is particularly relevant for large-scale landscape projects where representational validity and the ability to view the scene from different paths are required. The number of potential viewpoints can be increased by using 360-degree video rendering, even if the camera trajectory remains fixed. The advantage is that the entire scene does not need to be modeled, while the specific features requiring high precision are preserved. This approach may be partially superseded by Neural Radiance Fields (NeRF) technologies in the future.

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Designing with Hands: Hand-Tracking Interaction for Urban and Landscape Design in Virtual Reality

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Abstract: Hand tracking enables more direct, embodied interaction in virtual reality (VR), yet its practical value for creating urban and landscape design interventions remains under-examined. This paper presents a VR simulator that enables users to explore a site and propose spatial interventions through hand-tracking interaction, transforming design into an embodied act of spatial exploration and making. A pilot user study (N=5) examined the simulator's usability and user experience. Results suggest that hand tracking supports the full interaction and provides practical advantages during immersive design activity. This paper contributes a hand-tracking-enabled VR interaction approach and derives design implications for accessible urban and landscape design with lay participants.

Keywords: Virtual Reality, hand tracking, simulator, participatory design

1 Introduction

Virtual reality (VR) has become an increasingly important medium for urban and landscape design, offering immersive spatial exploration and interactive visualization that can extend beyond professional studios toward broader public engagement (PORTMAN et al. 2015). In participatory design contexts, however, the value of VR depends not only on what is visualized, but on who can meaningfully act within the environment. The ways people interact in virtual space shape how they understand spatial conditions, express preferences, and translate everyday needs into design moves. Conventional VR systems typically rely on handheld controllers mapped to button inputs, which convert spatial intent into abstract operations. This separation can introduce a cognitive and practical gap between bodily movement and spatial action, raising the interaction threshold for non-experts and potentially creating a barrier for participants without prior controller familiarity.

Hand-tracking technology presents an alternative paradigm that aligns more closely with participatory goals. By recognizing and interpreting natural hand gestures, it reduces reliance on intermediary devices and supports a more direct form of physical authorship in digital space (BUCKINGHAM 2021). For lay participants, this can lower the entry barrier by allowing interaction to build on familiar embodied skills: pointing, reaching, placing, and gesturing, rather than on learned button mappings. As a result, hand tracking may help participants engage more confidently, sustain attention on spatial decision-making rather than interface translation, and contribute design interventions that better reflect lived experience and situated knowledge.

This paper presents a VR simulator and hand-tracking interaction framework for urban and landscape design interventions. The framework treats navigation as a foundational act of spatial perception and supports four interaction methods: gesture-based vegetation planting, urban feature placement and manipulation, creative placeholders with semantic annotation, and sphere-triggered surface editing. The system operationalizes these methods through a design toolkit and contextual editing mechanisms, and it is evaluated in a formative qualitative pilot

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that compares hand tracking and controller input. Observation and post-session interviews were used to clarify how hand tracking supports design actions in VR and to examine its participatory and educational potential. This work contributes a validated simulator prototype and empirical evidence that characterizes modality trade-offs, informing design implications for future participatory design tools.

2 From Immersive Visualization to Embodied Design in VR

Immersive visualization has long been used in architecture and urban design to communicate proposals, test spatial scenarios, and support stakeholder understanding (PORTMAN et al. 2015). In participatory planning, however, many tools still privilege consultation over co-creation, where non-experts respond to options rather than shape them. SANDERS (2002) articulated this need of to shift from "designing for users" to "designing with users," moving beyond user-centred approaches toward participatory experiences where stakeholders become active co-creators. VR can shift this balance by enabling participants to not only see alternatives but also compose them by placing elements, adjusting configurations, and iterating proposals in situ (CHOWDHURY & SCHNABEL 2019, VAN LEEUWEN et al. 2018), bringing participatory input closer to design activity rather than feedback alone.

This shift matters because architectural and urban understanding is fundamentally experiential. Place is grasped through movement, changing viewpoints, and bodily presence (MALININ 2016), and design judgment often develops through iterative reflection while acting within a situation (DOURISH 2001, SCHÖN 2017). For VR-based participatory design, this implies that interaction should support multi-perspectival navigation and direct interaction and manipulation with the virtual environment. From this perspective, hand tracking may lower the participation threshold for non-experts by aligning interaction with familiar bodily skills (BUCKINGHAM 2021), helping participants concentrate on spatial intent and design needs.

3 VR Simulator Design and Interaction Framework

3.1 System Overview

A VR simulator was developed in Unity using Meta's All-in-One SDK for hand-tracking implementation and was tested on a Meta Quest 3 headset. The simulator reconstructs the residential district centred on the upcoming transit station at Nanyang Technological University, including surrounding student plazas and green spaces. The intent is not hyper-realistic replication, but a responsive and coherent spatial setting that supports immersion and meaningful creation and editing actions. The simulator features a three-level structure and includes a central design toolkit for design interactions.

3.2 Navigation and Locomotion

The simulator provides three hand-gesture-based locomotion modes: teleportation, continuous sliding, and snap turning. Teleportation uses a pinch gesture: users stretch the index finger and thumb to indicate a destination and pinch to move instantly. Continuous movement

is controlled through a thumb-up gesture to slide forward and a thumb-down to move backward. Snap turning allows users to rotate their viewpoint using a pinch gesture on the directional turning arrow, triggered by extending the thumb and index finger. A hand menu is attached to the user's left hand to access the design toolkit and system control (Figure 1).

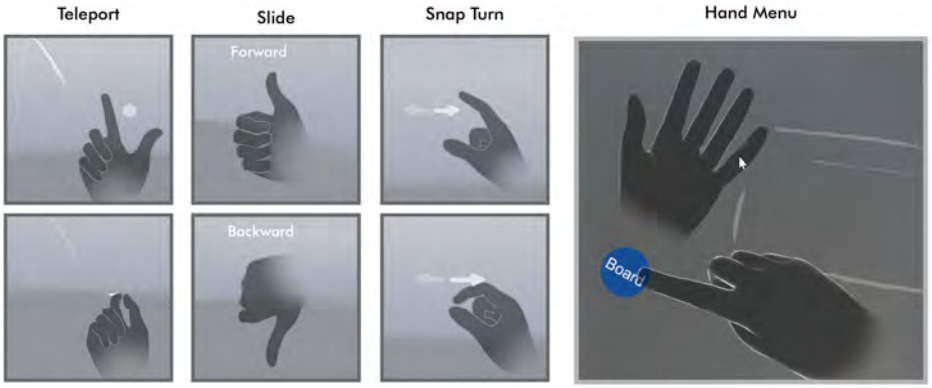

Fig. 1: Hand gestures for Navigation (Teleport, Slide and Snap Turn). Hand Menu is attached to the left hand and toggled through the wrist button.

3.3 The Design Toolkit

The simulator incorporates a layered design toolkit that enables users to make spatial interventions and modify the virtual environment. The toolkit consists of two integrated components: a hand-mounted menu containing eight categories of urban assets, and scene-embedded triggers covering two additional asset categories. Each category includes associated assets and editable properties, including style variants, transforms (position, rotation, scale), materials, and open-end annotations. Figure 2 shows the hand-mounted design toolkit.

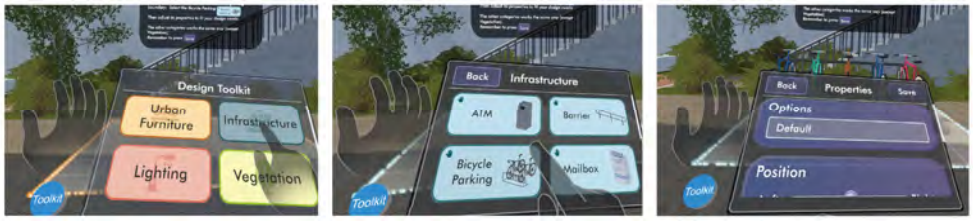

Fig. 2: Hand-mounted toolkit UI: category (left), asset (middle), and property (right)

The hand-menu assets include categories such as Vegetation (planted within designated area), Urban Furniture, Infrastructure, Installation Art, Playground, info, Lighting and Customized, which can be spawned and repositioned directly within the scene. The scene-embedded triggers support Pavement and Architectural Façade (allowing users to annotate indoor space) modification. These assets operate at a larger spatial scale, focusing on material transformation and spatial function changes.

3.4 Design Interaction Framework

The simulator supports full hand-tracking interaction through four complementary paradigms with the design toolkit and representative in-VR screenshots are shown in Figure 3.

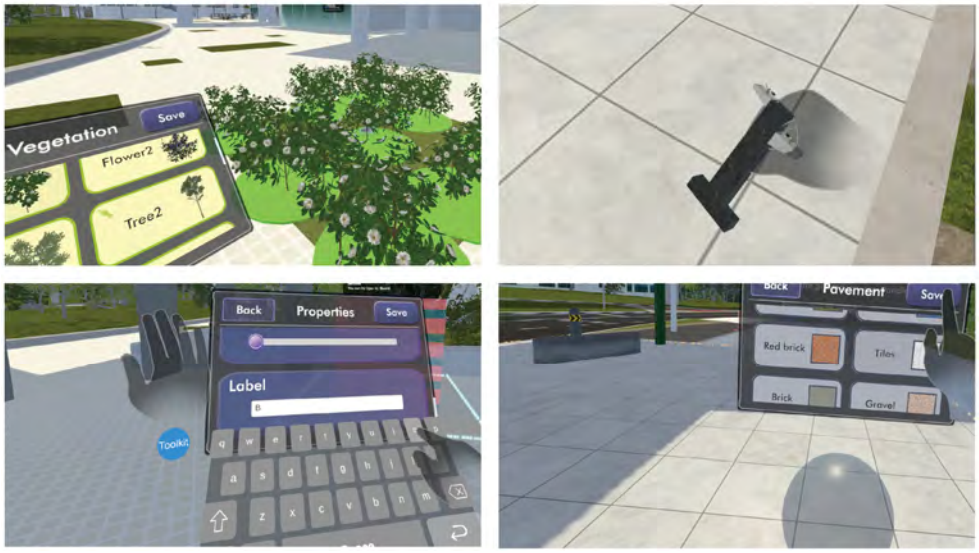

Fig. 3: 1) Gesture-based Vegetation Planting (top left), 2) Urban Feature Direct Placement (top right, The UI interaction is shown in Figure 2, this image illustrates direct hand-grab placement), 3) Creative placeholder with semantic annotation (bottom left), 4) Sphere-triggered surface editing (bottom right)

1) Gesture-based Vegetation Planting – Users use a pinch gesture (thumb and index finger) to select vegetation planting areas on the grass field; pinching again deselects the area. Once an area is selected, users choose a vegetation asset from the hand menu toolkit, and plant it within the designated zone.

2) Urban Feature Direct Placement – Users select assets via buttons on the hand menu; the selected asset is instantiated five meters in front of the camera, and the hand menu opens the property interface to adjust its parameters. Instantiated assets can also be manipulated directly via hand interaction: users grab an object with one hand while navigating with the other to reposition and align it within the environment. During grabbing, assets are automatically scaled to a hand-held proportion to reduce visual occlusion.

3) Creative placeholder with semantic annotation – Users can press the Customized button to place a cube as a placeholder to propose a specific asset not available in the toolkit. Besides transformation and material adjustments, they can annotate it via a virtual keyboard to label intended functions or design ideas directly in the virtual scene.

4) Sphere-triggered surface editing – Users touch floating spheres placed in the environment to open contextual UI panels for surface customization, such as changing pavement materials. This interaction encourages focused attention on ground texture, continuity, and material composition in public-space design. The same approach is applied to architectural

façade modification, which additionally includes an annotation feature that allows users to type ideas or proposed functions for interior spaces directly within the virtual scene.

All interactions are also mapped to controllers for equivalent functionality.

3.5 Levels and Procedure

Level 1 (Explore) supports spatial familiarization through navigation. Participants traverse the virtual site to four designated checkpoints to build spatial understanding.

Level 2 (Guided challenges) provides four framework-aligned tasks as a tutorial. It scaffolds use of the design toolkit, with each interaction method introduced as one guided challenge.

Level 3 (Sandbox design) is an open-ended phase that integrates Levels 1 and 2 into a single design loop. Participants freely navigate to assess spatial conditions and implement interventions with the toolkit.

4 Pilot Study Design and Analysis

A formative qualitative pilot was conducted with five participants from the school community (P1-P5) to assess feasibility and inform refinements to the simulator and its interaction design. Participants varied in prior experience: P1, P2 had both VR and spatial design experience; P3 had VR experience only; and P4, P5 had neither. The session followed a three-level workflow. In Level 3, participants first continued designing with the hand tracking and were then provided with the controller during the middle-to-late stage of the session to try the same interactions and make an immediate comparison.

Duration was recorded for each level. Qualitative data were collected through in-session observation and a post-session interview. Observation focused on learnability and interaction breakdowns as participants navigated, used the hand menu, selected and manipulated assets, and performed contextual editing. The interview elicited comparative reflections on naturalness, ease of use, enjoyment, and frustrations for hand tracking versus controller input, grounded in the interaction paradigms. Participants were also asked what they liked most about hand tracking in the simulator, what they disliked or struggled with most, and to describe one concrete moment from the session that illustrated their view.

Observation notes and interview responses were consolidated after each session and analysed using a rapid qualitative approach. Recurring issues and positive affordances were grouped into themes and organized by interaction component (navigation and the four interaction paradigms) and by input modality (hand tracking vs. controller) to capture context-specific trade-offs. Themes were then synthesized across participants to identify consistent patterns and illustrative moments, and findings are reported as formative insights that informed iterative refinements and motivated design implications.

5 Results

For the five pilot participants, Level 1 duration had a median of 4.95 min (range 3.32-6.77), and Level 2 duration had a median of 9.03 min (range 5.87-14.27). Level 3 duration depends

on participants' performance, with participants typically producing around 8-10 design interventions on average. In this pilot, Level 3 lasted a median of 17.53 min (range 12.98-27.20). All participants completed the full three-level session within approximately 22.17-46.42 min.

In-session observation showed that participants generally became more fluent using hand gesture after a short familiarization period. The most common breakdown under hand tracking was unintended UI activation, where participants mis-touched or mis-selected interface elements when interacting with menus and panels. Gesture recognition was also sensitive to how standard the gesture was performed: snap-turn gestures were sometimes not detected reliably, leading several participants to turn physically instead. Another observed issue was that some participants held a gesture posture even when not intending to trigger an action; when switching to a different gesture, the previous gesture could remain active and interfere with recognition, making mid-task transitions feel effortful. In moments of uncertainty, participants occasionally confused gestures and required reminders, particularly when transitioning between commands. This also happens when participants switched to the controller during Level 3, those with prior VR experience adapted quickly and regained stable interaction with minimal guidance. In contrast, the VR-novice participants required additional time to recall controller mappings and showed more hesitation during early controller use.

Interview responses aligned with the observed patterns and indicated modality-dependent trade-offs across navigation and the four interaction paradigms. Participants with prior VR experience (P1, P3) found the controller faster and more precise, and P1 described it as natural and easy once familiar mappings were learned, particularly for stable selection. For navigation, participants generally reported that the controller was easier, faster, and more precise for moving through the site. Across paradigms that relied on UI elements, participant P5 described hand-based UI interaction as "like a touchscreen," and all participants described hand tracking as more fun and intuitive, especially for directly grabbing and manipulating objects.

At the same time, differences emerged by paradigm. For vegetation area selection (Paradigm 1), all participants indicated that the controller was easier because button press was faster and more reliable than performing a pinch gesture. For the hand-menu-dominated interaction (Paradigm 2), hand tracking was preferred because direct finger-based interaction felt more immediate. For Paradigm 3, participants reported that hand input felt natural for typing but was constrained by stability demands: the hand-mounted keyboard was often described as difficult because the hands could not always be held steady. Similarly, surface editing with annotation in Paradigm 4 also involved text input, and participants reported that hand tracking was easy to use when the keyboard was stable and clearly anchored in the scene.

6 Discussion and Conclusion

The formative pilot indicates that the simulator is feasible for the targeted urban and landscape design tasks. All participants completed the three-level workflow within a single session, and hand-tracking supported the intended operations for spatial navigation, toolkit-based design interventions and contextual editing. Observed issues were primarily matters of tracking accuracy and sensitivity rather than failures that prevented participants from completing design tasks. Modality preference varied with prior VR experience: experienced participants tended to prefer controllers, while VR-novice participants engaged more smoothly

with hand tracking. This suggests that familiarity with controller mappings and confirmation logic influenced perceived ease of interaction across input modalities in this pilot. Even though controller input was only introduced later in Level 3, these VR-novice participants still judged hand tracking as sufficient for completing the design operations, implying that the controller's potential advantage was not decisive in their case.

The simulator underscores the importance of the virtual environment as a medium for urban and landscape design. Experiencing the site at human scale lets lay participants test interventions in context and understand spatial relationships beyond static representations. This situated setting supports design judgment because interventions can be assessed embodied against the existing spatial configuration and perceived qualities of the place (SCHÖN 2017). Within this environment, first-person navigation is central, particularly because urban and landscape sites operate at relatively large scales. Moving through the scene across key areas helps participants develop spatial understanding of distance, adjacency, and scale, and supports checking of interventions in context (LYNCH 1960).

Building on this spatial grounding, hand tracking can further strengthen the simulator's suitability for participatory design by lowering the interaction barrier and increasing enjoyment. In this pilot, participants with no VR experience and no spatial design experience were still able to produce spatial interventions in Level 3 and described the process as enjoyable. Hand tracking aligns interaction with familiar embodied skills, shifting attention from memorizing mappings to expressing spatial intent. In this sense, "fun" supports sustained engagement and encourages non-experts to explore, intervene, and iterate within the virtual environment.

Earlier gesture-based systems in design contexts often treat gestures as a general-purpose alternative for selection and manipulation (MASUROVSKY et al. 2020). This work differs by operationalizing hand tracking as a comprehensive workflow for site-scale urban and landscape design, combining first-person navigation with hand-based interaction through a tailored design toolkit for contextual editing. The contribution lies in the interaction structure that links toolkit-based interventions and in-situ evaluation through repeated movement and iteration, rather than proposing gestures as a standalone input technique.

This formative pilot has clear limitations. First, hand tracking still showed occasional accuracy and sensitivity issues, indicating scope to improve gesture design and interaction stability. Second, the sample was small (N = 5). As an initial step, this pilot primarily assessed the simulator from a usability perspective. Future work should run larger, structured studies to confirm usability and to test whether the simulator effectively supports participatory design outcomes across users spanning different levels of VR and spatial design experience.

In summary, this paper introduced a VR simulator that operationalizes a hand-tracking interaction framework for urban and landscape design through toolkit-based interventions and contextual editing. The formative pilot suggests the system can support urban and landscape design activity in a first-person, human-scale environment, while revealing practical trade-offs between hand tracking and controllers that inform interaction design. Overall, the pilot points to hand tracking as a potentially accessible input modality for lay participants, supporting task completion and iterative exploration in participatory spatial design.

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Examining Anthropocentric Stimuli and Streetscape Design Using Virtual Reality

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Abstract: Understanding how people perceive and emotionally respond to built environments is a challenge in landscape and environmental design due to the difficulty of isolating specific design variables from changing sensory and social conditions. Virtual reality (VR) offers a powerful solution to this challenge by providing immersive yet controlled environments. Using VR and quantitative approaches, this study investigates how different levels of human activation in a built environment affect people's perception of street physical elements and their emotional responses to the streetscape through sense of place. Results indicate that varying levels of human activation did not produce significant differences in perceptual load or sense of place. However, environments with higher human activation exhibited stronger and more predominantly negative relationships between perceptual load variables and sense of place.

Keywords: Virtual reality, visual stimuli, perceptual load, sense of place, urban vibrancy, multi-use streetscape, environmental psychology

1 Introduction

Outdoor environments vary by weather, time of day, sensory stimulation, and external conditions which makes it difficult to isolate how people respond to specific site design variables. To address this challenge, researchers are increasingly using emerging methods such as virtual reality (CROCKER et al. 2025, MARTINEZ et al. 2024). However, these studies have examined responses to built form changes, not to the activation of a site. While research in environmental psychology and urban design has explored the effects of human congestion in public space (e. g. SIMOES AELBRECHT 2023), crowding perceptions (e. g. ZHANG et al. 2023), and social carrying capacity (e. g. MANNING et al. 2010), relatively few studies have tied these metrics directly to specific design attributes and an overall sense of place in outdoor environments. This study explores these gaps by using virtual reality (VR) to examine how varying levels of anthropocentric stimuli, defined as the number of people visible and associated stimulation, relate to perceptions of the site design elements and the site experience.

Perception is the ability to detect structures and events in one's surroundings and plays a crucial role in how people engage with an urban environment (BRUCE et al. 2003). Site elements such as lighting, planting, furniture, paving, and the presence of people contribute to a multisensory experience that shapes a person's sense of place. Evidence remains limited on how users perceive physical elements in relation to the presence of other humans in the same space.

Building on perception as a transactional view that emphasizes active visual attention (PERVIN 1978), this study uses VR and post-experience surveys to examine links among anthropocentric visual stimuli, tangible streetscape elements, site perceptions, and sense of place in a mixed-use environment. Specifically, the study addresses the following overarch-

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ing research questions: 1) How do different levels of anthropocentric stimuli in a streetscape influence users' perceptual and experiential responses, including awareness of design elements, distraction level, place experience, and sense of place? 2) How are these perceptual and experiential responses interrelated under different levels of anthropocentric stimuli?

2 Methods

2.1 Virtual Reality Experiences

Immersive VR allows for an individual to experience a planned and consistent environment in which designers can pre-meditate to produce the ideal testing environment (BOWMAN & MCMAHAN 2007, GEORGE et al. 2022). For this study, VR was used to simulate a mixed-use streetscape environment including humans actively using the space. VR was used over a real-world setting to control for variables. Higher education student participants, primarily recruited via a college listserv email, experienced a 360-degree video of a streetscape block using a VR headset with one of two environments which included either a high or low level of anthropocentric stimuli (Figure 1 & Figure 2). A consistent mixed-use streetscape base

Fig. 1: An aerial perspective highlights the VR study path

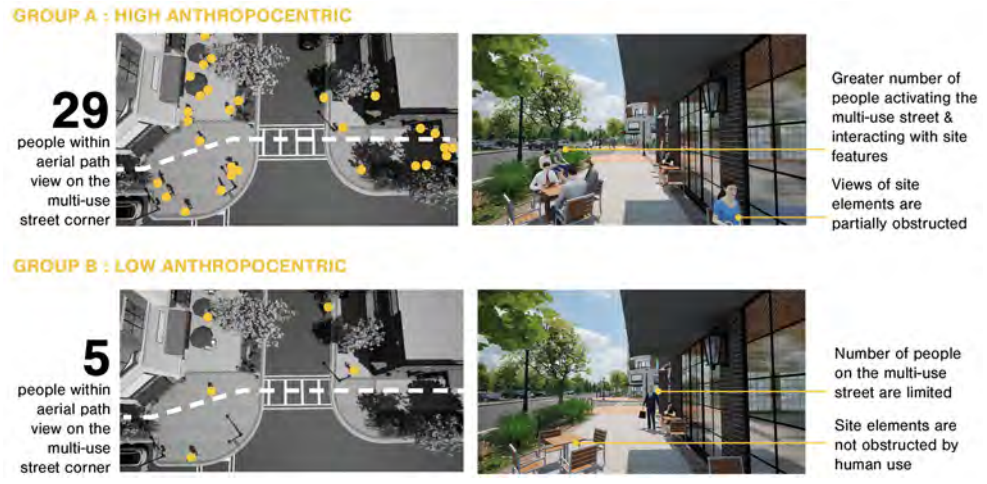

Fig. 2: A plan and pedestrian view of each environment showing the difference of anthropocentric levels in relation to streetscape elements. Group A included 67 people across the streetscape environment and Group B had 18 people. Distribution and quantity were based on a site observation of people in a similar urban environment.

was used in both environments, and the changing variable between study groups was solely the amount of people. Half of the participants experienced high levels of anthropocentric stimuli (Group A), and the other low anthropocentric stimuli (Group B).

2.2 Survey

Post-VR experience, study participants were asked to complete an online survey to aid in the understanding of participants' perceptions including questions measuring sense of place (SOP) and perceptual load (Table 1). SOP is a multidimensional construct reflecting beliefs, emotions, and behavioural commitments tied to a particular setting (JORGENSEN & STEDMAN 2006). Perceptual load is defined as the prioritization of selectively processing relevant information while filtering competing environmental stimuli (LAVIE 1995) and was assessed through recall-based questions about site elements, as well as questions on the distraction of people in the environment and place experience (Table 1).

Table 1: Survey design of study variables. A Likert scale was used based on existing measurement scales and questions. Demographic and other additional questions not included.

Measure	Survey Question	Justification
Sense of Place		
Place Attachment	I feel relaxed in this place.	JORGENSEN & STEDMAN 2006
	I have at least one special memory in an environment like this.	
Place Quality	When I think of a successful streetscape this place comes to mind.	CASAKIN & NEIKRUG 2012
	The general look and feel of the streetscape works well here.	
Place Familiarity	I often come to places that look like this one.	RAYMOND et al. 2017
	I have visited places that have looked like this before.	
Place Meaning	There are objects within this streetscape that have a symbolic meaning to me.	
	My personal experiences shape how I engage with an environment like this one.	
Perceptual Load		
Awareness of Design Elements	Rate how much you noticed each landscape feature within the environment: a. Lighting Fixtures (street light poles, exterior building lights), b. Plantings (trees, shrubs, other plantings), c. Paving (brick paving, concrete walks), d. Street Furnishings (benches, trash receptacles).	VARAT 2010, PULSIPHER et al. 2020
Distraction Level	The people are a distraction in this environment.	BRUCE et al. 2003, STOJANOVSKI & AXELSSON 2019
Place Experience	Fewer people in this environment would positively affect my experience.	

2.3 Methods of Analysis

The analysis consisted of two complementary quantitative approaches. First, inferential statistical tests were used to compare mean values across two VR environments that differ in their levels of anthropocentric stimuli. The comparisons focused on four variables, including two composite constructs and two single-item measures. Awareness of design elements was operationalized as a composite score calculated as the average of participants' self-reported

awareness of planting, lighting, furniture, and paving. SOP was operationalized as a composite score averaging place attachment, place quality, place familiarity, and place meaning, each constructed as the average of two survey items. SOP internal consistency was assessed at the item level across the eight SOP items. In contrast, distraction level and place experience were treated as single-item measures, each assessed using one survey question.

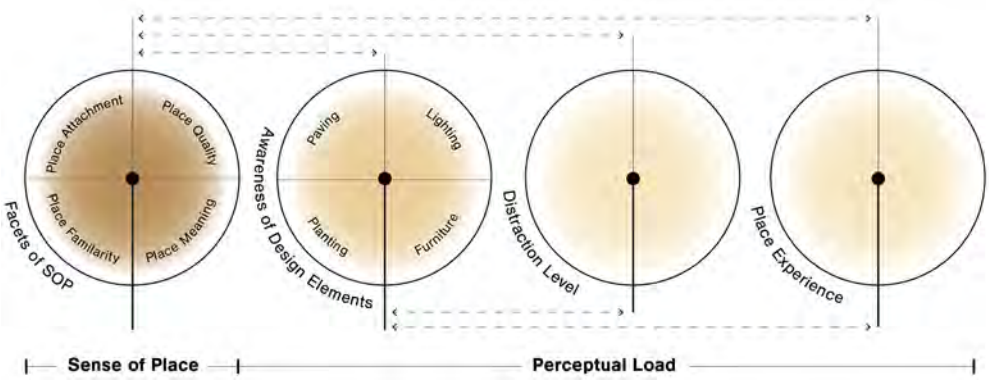

Fig. 3: Framework of Analysis. A graphic representation of the main facets guiding the experimental study. Circles represent variables and dashed lines the relationships explored. Design elements were selected from established streetscape guidelines (SAN FRANCISCO PLANNING DEPARTMENT 2010).

Depending on the normality of each variable, either independent-samples t-tests or Wilcoxon rank-sum tests were applied. Second, Spearman rank-order correlations were conducted separately within each VR environment to examine associations among the four variables. These analyses were selected to address the research questions by enabling both between-environment comparisons and within-environment associations among key variables.

3 Results

3.1 Descriptive Statistics of Participant Demographics

A total of 104 participants, mostly university students from design-related backgrounds, experienced one of two VR streetscape environments characterized by different levels of anthropocentric stimuli. Participant demographic characteristics are summarized in Figure 4. Of the total sample, 53 participants experienced high anthropocentric stimuli (Group A), and 51 participants experienced low (Group B). Participants were primarily young adults, with most between 18 and 23 years of age. The sample was largely white (69.2%) and predominantly female (61.5%). Most participants reported some prior VR experience, with 64.4% indicating yearly use and 7.7% monthly use, while 24% reported no prior use.

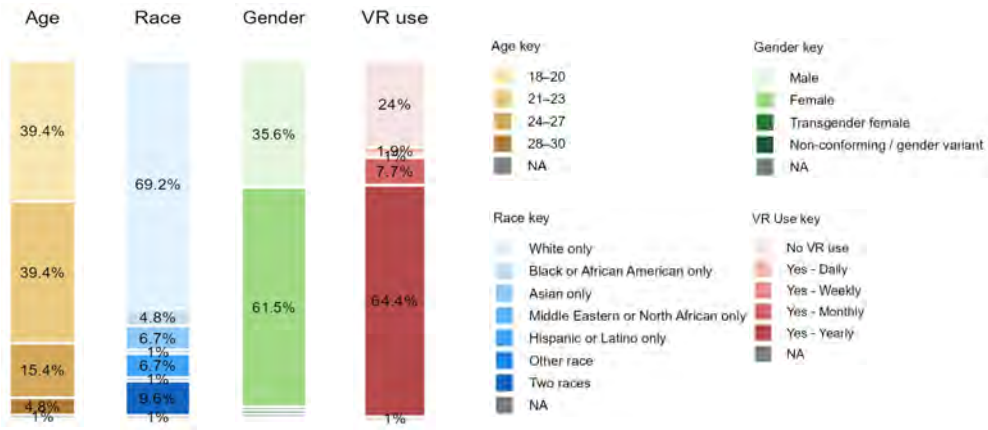

Fig. 4: Percentage distribution of participant demographic characteristics. Categories with zero observations are not included.

3.2 Effects of Anthropocentric Stimuli on Perceptual Load and Sense of Place

Within the perceptual load concept, the effects of anthropocentric stimuli levels on awareness of design elements, distraction, and place experience were examined. Shapiro-Wilk tests indicated non-normality in awareness scores for one group and in distraction and place experience scores for both groups; therefore, Wilcoxon rank-sum tests were applied. The awareness construct, which showed acceptable internal consistency (Cronbach's $\alpha = .65$), did not differ significantly between groups (Group A: M = 3.44; Group B: M = 3.67; $p = .171$), and the associated effect size was small (r = .14, 95% CI [.01, .32]). Distraction scores were higher in Group A (M = 3.42) than in Group B (M = 2.96) with a marginal difference ($p = .052$) and a small effect size (r = .19, 95% CI [.02, .36])., Place experience also did not differ significantly between groups (Group A: M = 3.09; Group B: M = 2.78; $p = .211$), and the effect size was small (r = .12, 95% CI [.01, .31]), Across perceptual load facets, effect sizes were small (r = .12–.19) with wide confidence intervals, indicating weak and uncertain group differences.

SOP scores, which demonstrated acceptable internal consistency at the item level (Cronbach's $\alpha = .63$), were normally distributed in both groups (Shapiro–Wilk $p = .399$ and .467), as a result, an independent-samples *t*-test was conducted. SOP scores were slightly higher in Group B (M = 4.00) than in Group A (M = 3.93), but the difference was not statistically significant, $t(101.83) = -0.75$, $p = .45$, with a small effect size (d = −0.15, 95% CI [−0.53, 0.24]). All four SOP facets exhibited non-normal distributions, and Wilcoxon rank-sum tests indicated no significant group differences across facets (all $p > .05$). Effect sizes were small (r = .04–.11) with wide confidence intervals, suggesting limited evidence for meaningful group differences. **In sum, varying levels of anthropocentric stimuli were not associated with statistically significant differences in perceptual loads and SOP or its facets.**

3.3 Associations Among Perceptual Load and SOP

Spearman correlation analyses revealed distinct perceptual patterns between the two groups of participants (Figure 5). In Group A, higher awareness of streetscape design elements was moderately associated with lower perceived distraction by people (ρ = -.43, p = .001) and lower agreement that fewer people would improve the experience (ρ = -.42, p = .002), while relating positively to SOP (ρ = .43, p = .001) and place quality (ρ = .37, p = .006). However, in this group, greater agreement that fewer people would improve the experience was negatively associated with SOP and its components, including place attachment and place quality (ρ range = -.36 to -.40, p range = .003 to .008).

In contrast, Group B showed no significant associations between awareness and perceptual load variables, but a more positive relationship with SOP and place quality. Specifically, agreement that fewer people would improve the experience was positively associated with SOP (ρ = .29, p = .038) and place familiarity (ρ = .41, p = .003), while perceived distraction by people was negatively related to place attachment (ρ = -.35, p = .012).

Overall, the environment with higher anthropocentric stimuli exhibited stronger and more predominantly negative relationships between perceptual load variables and SOP, whereas the environment with lower anthropocentric stimuli showed weaker but more consistently positive associations.

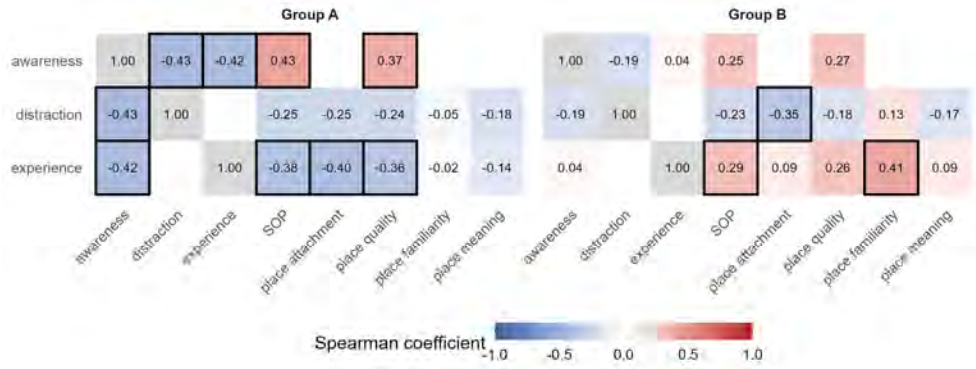

Fig. 5: Spearman correlation results for Group A and Group B. Cell values represent correlation coefficients, with outlined cells indicating statistical significance ($p < .05$). Pairwise correlations not central to the study focus were removed for clarity.

4 Discussion and Conclusion

This study advances a VR-based approach that isolates the experiential role of human activation by varying the number of people in lifelike streetscapes while holding physical and sensory conditions constant. The method creates a controlled yet immersive setting that allows inferences about activation without confounds from weather, time of day, or incidental noise. Within this framework, composite SOP did not differ meaningfully across activation levels, suggesting that additional human presence may not, on its own, elevate place attachment, meaning, quality, or familiarity. At the same time, the controlled exposures clarify how SOP aligns with tangible design choices and the character of social experience rather than

with the quantity of people alone. Although overall SOP scores were similar across conditions, differences in activation level were reflected in the relationships between perceptual load and SOP, with higher anthropocentric stimuli associated with more negative experiential relationships.

These insights have practical implications for design and evaluation. They suggest that a person's SOP may rely more on the physical environment than current literature suggests, including the structure and quality of planting, paving, furnishings, and lighting. They also position VR as a practical testbed for pretesting design guidelines and calibrating activation goals to specific site configurations before implementation. Designers can use this approach to compare alternative scenarios under consistent conditions, weigh trade-offs between vibrancy and experiential quality, and refine guidelines with evidence that is replicable and interpretable for practice. By deepening understanding of how users perceive multi-use streetscapes, designers are better equipped to create environments that are visually and emotionally appealing, with many opportunities to improve tangible features that leave positive, lasting impressions.

Future studies could add a VR environment with no people as a control condition and test a wider range of anthropocentric stimuli. In addition, because SOP can be linked to attachment and familiarity with a specific place or place type, incorporating more recognizable or participant relevant details into the streetscape design, or using a more familiar setting, may influence SOP outcomes. Future work could also isolate specific design variables independently and in more detail, such as planting structure, placement, and species, to produce clearer evidence that can inform urban design guidelines. Finally, researchers could examine thresholds of anthropocentric stimuli in relation to awareness of design elements and SOP to better understand ideal urban streetscape conditions for different goals.

There are several limitations to this study. VR constrained the sensory realism of the streetscapes, which may alter SOP responses compared with real settings, and the representation of people and movement was limited to projected visuals rather than embodied interaction. People counts and their spatial distribution across the study environments were derived from a site observation of a similar environment conducted during this exploratory study. Future studies could examine this dimension more rigorously through systematic sampling and measurement. As prior research asserts, even realistic virtual representations may not be perceived as intended (LANGE 2011). Novelty effects are possible for participants with little prior VR exposure, even though the viewing was repeated to support acclimation. Controlled scenes also bracket day-to-day variability in weather and ambient activity, so findings may shift under real-world conditions. In addition, the cross-sectional and exploratory nature of the analyses limits causal inference. Reliance on self-reported measures with modest internal consistency for the composite SOP construct may constrain the precision of observed relationships, suggesting that observed associations should be interpreted cautiously. Nevertheless, the study sheds light on how stimuli can affect individuals' perceptions of streetscapes and demonstrates the unique value of VR for testing the influence of activated site conditions.

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Comparative Assessment of the Cognitive Effectiveness of Projection Mapping on Physical Models Versus Digital Renders in Landscape Architecture

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Abstract: Projection mapping (PM) on physical models offers a hybrid representational medium for landscape architecture, yet its influence on spatial cognition remains under-explored. Through a comparative assessment using cognitive maps and surveys, the cognitive efficiency of PM on physical models is evaluated against conventional digital renderings among a cross-stakeholder group of participants, including 30 landscape architecture students and 10 educators. This research provides empirical evidence for PM's role in enhancing spatial communication and offers insights into its potential to support the landscape design process.

Keywords: Projection mapping, spatial cognition, cognitive maps, representation methods, landscape architecture

1 Introduction

Design in landscape architecture involves a dialogue between analysis, synthesis, and evaluation, requiring designers to continuously interpret spatial relationships across multiple scales. Physical models have traditionally played a crucial role in this process by supporting spatial comprehension, topographic understanding, and perceptual engagement. Nevertheless, once constructed, physical models can be time-consuming and costly to modify, particularly in educational settings where rapid response to critiques is essential. Consequently, this process has been further accelerated by the widespread adoption of digital technologies across various disciplines. 3D models and rendered images have become widely adopted in landscape architecture education and practice due to their efficiency (AMOROSO 2015).

While these tools enable rapid modification and visual realism, research suggests that highly polished digital renderings may encourage a focus on image quality rather than on spatial structure, ecological processes, or technical reasoning. This limitation underscores Oxman's (2006) theory that design in the digital age requires a critical evaluation of how representational tools influence design thinking, as highly refined visuals may reduce the interpretative depth required for complex site analysis. As TVERSKY (2005) notes, the functional significance of spatial thinking is dictated by the medium; different representations can either facilitate or obscure the mental rotation and spatial orientation necessary for effective landscape evaluation.

Projection mapping (PM) on physical models offers a hybrid approach by combining the material presence of physical models with the adaptability of digital content. In this article, PM is utilized as a form of spatial augmented reality (SAR) to overlay physical models with dynamic information. This application of SAR, defined by BIMBER & RASKAR (2005) as the

merging of physical and virtual worlds, allows designers to visualize multiple layers of information, such as historical physical-scale data, without requiring repeated physical reconstruction. Such a hybrid medium aligns with James Corner's (1999) concept of the "agency of mapping," where representation is viewed as a process-oriented tool that supports a deeper understanding of landscape systems rather than a static image.

The cognitive effectiveness of this hybrid medium is further grounded in the fact that physical engagement improves 3D conceptualization, as argued by PASSIG & EDEN (2000). Furthermore, the non-isolated nature of the physical model promotes "situatedness" and collaborative discourse, as theorized by MAHER & GERO (2002). This grounded spatial awareness is supported by Cognitive Load Theory (PAAS & SWELLER 2014) and the concept of the embodied mind (JELIĆ et al. 2016), which suggest that spatial orientation is most effective when digital layers are integrated into a tangible, physical context. Accordingly, this research aims to comparatively assess how PM on physical models and conventional digital renderings support spatial cognition in landscape architecture. To account for the impact of professional expertise, the assessment involves a group of 30 landscape architecture students and 10 experienced educators.

2 Reference Studies

With advances in digital technology and visual representation techniques, landscape architects have increasingly adopted three-dimensional modeling, rendering, and immersive visualization tools due to the discipline's reliance on communicating complex spatial relationships (MOURAL et al. 2018). While these tools enhance visual clarity and efficiency, their influence on spatial cognition and learning remains a subject of debate. Digital models and renderings are currently the most widely used representational media in landscape architecture (ASLA 2019). Yet, previous research has raised concerns that hyper-realistic digital renderings may reduce interpretative engagement and encourage surface-level evaluation of design proposals (KULLMANN 2014).

In parallel, studies in architecture, media art, and interaction design have explored PM as a tool for presentation, material representation, and collaborative design (CALIXTE & LECLERCQ 2017, MIYASHITA et al. 2018 TASTAN & TONG 2018). These studies demonstrate the technical and experiential potential of PM, yet primarily focus on interaction, visualization, or performative qualities rather than on cognitive outcomes. Landscape architecture requires the specific ability to visualize and evaluate spatial relationships among landscape components across different scales (CARBONELL-CARRERA et al. 2020).

Physical models remain important for understanding topography and spatial hierarchy (MOEINI & SHAVANDI 2015), and industry applications have increasingly adopted PM to enhance model-based presentations (e. g., the Kuala Lumpur Master Plan). According to WU et al. (2021), advancing technologies such as virtual reality (VR) enable designers to enhance viewers' spatial awareness through immersive environments. This increased awareness enables decision-makers and designers to visualize projects more effectively prior to implementation, thereby streamlining decision-making processes. However, experimental research examining how PM influences spatial cognition, particularly in comparison to established digital representations, remains limited. Based on this research's results, PM on a physical model

can serve as an additional immersive means of conveying design choices to designers and stakeholders, achieving rapid feedback.

3 Methodology

Research employed an experiment designed to evaluate the cognitive effectiveness of two representational media comparatively: rendered images of a digital three-dimensional model, as it is the most widely used medium in the field (ASLA 2019), and PM applied to a physical model of the same site (Figure 1). A total of 40 participants, comprising 30 landscape architecture students and 10 experienced educators, were randomly assigned to two balanced groups regarding their knowledge and experience levels (each including 15 students and 5 educators) to evaluate the influence of professional expertise on spatial cognition. Group 1 viewed rendered images, while Group 2 experienced projection mapping (PM) on the physical model (Figure 2).

Both groups had one minute to observe the site with the representation technique assigned to their group. Observation timeframe was selected as one minute, referring to SLIGTE et al.'s research (2008) that visual short-term memory (VSTM) is capable of retaining a limited amount of information typically within seconds, and ISHAI et al.'s research (2002) stating observation time extended to approximately 60 seconds contributes to a deeper processing of the stimuli, beyond short-term memory.

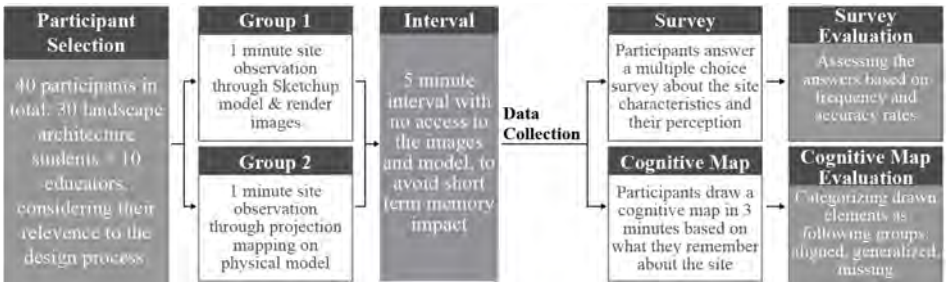

Fig. 1: Experiment design

To serve as an example site for participants to observe, a physical site was intentionally avoided to minimize potential prior knowledge and familiarity bias. Instead, researchers designed a site that incorporated spatial characteristics commonly examined in landscape architecture (HUANG et al. 2025, ŞENTÜRK & ALTINÇEKIÇ 2018), such as settlement typologies, hierarchical road networks, elevation contours, a water element, and vegetation. These features were selected to allow assessment of both structural and detailed spatial understanding across representation types. For Group 1, the designed site was modeled in SketchUp, due to its wider use in the industry (GEORGE & SUMMERLIN 2019), and for Group 2, a physical model out of white cardboard was produced, and the site plan was reflected on the model as PM, using the Adobe After Effects program (Figure 3). In this setup, settlement structures were constructed as 3D physical masses to ensure the medium provided structural depth rather than just surface-projected shapes.

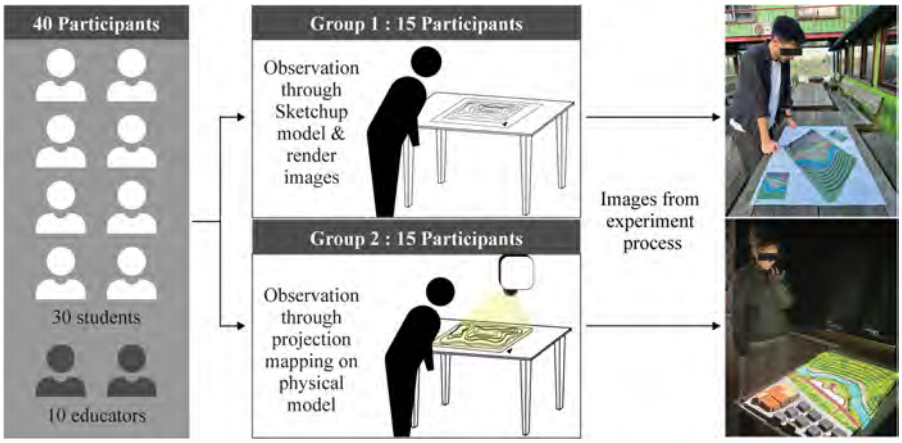

Fig. 2: Participants' observation groups and real-time experiment photos

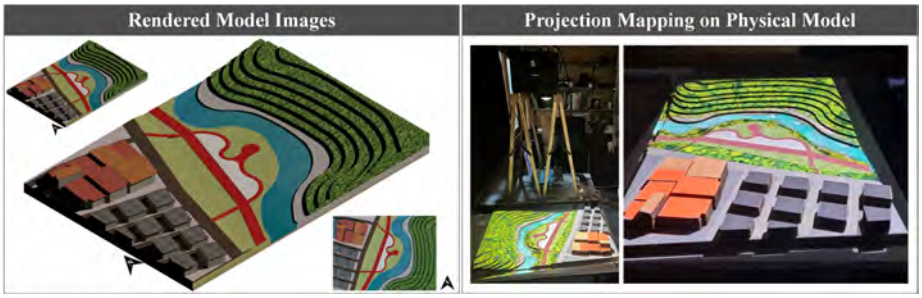

Fig. 3: Plan of the designed site, rendered model images, and projection mapping on a physical model setup

Following HEGARTY et al.'s research on spatial-layout learning (2006) and POSTMA'S research on visual object locations (2000), participants were given a 5-minute interval after the observation phase to ensure that spatial learning was measured rather than visual recall or short-term memory. After the interval, participants were asked to draw a cognitive map of the site from memory. Pilot testing indicated that three minutes provided sufficient time for participants to produce maps suitable for comparative evaluation. Cognitive maps were assessed using criteria adapted from SCHWERING et al. (2022), with emphasis on the completeness and accuracy of site elements (Figure 4).

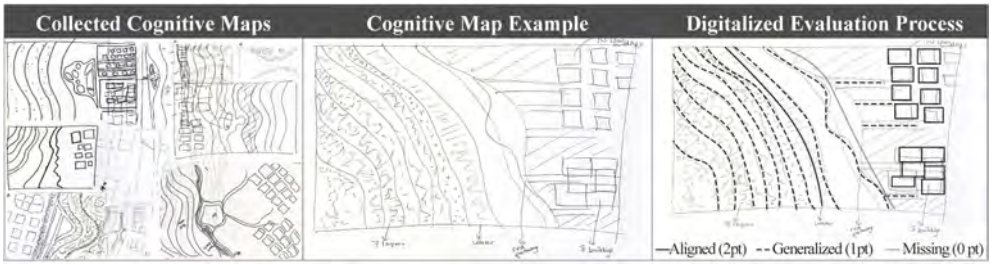

Fig. 4: Cognitive map evaluation system adapted from SCHWERING et al. (2022), assessing the drawn features in 3 groups (the features are accurate and positioned close to the actual locations: aligned = 2 points, the futures are either accurately drawn or placed close to the exact locations: generalized = 1 points, not drawn at all: missing = 0 points) after digitalizing

In the final phase, participants completed a structured questionnaire comprising multiple-choice and rating-scale items regarding general zoning relationships, quantitative aspects of site elements, and material identification. Participants also provided brief written comments on the perceived effectiveness of the representation medium. While the analysis of cognitive maps necessarily involves researcher interpretation, the study follows a two-phased cross-examination process, integrating descriptive and comparative analytical data from the survey to identify observable trends in spatial cognition.

4 Results

Analysis of the drawn cognitive maps' evaluation (Figure 5), indicates that both groups demonstrated similar levels of element recall, with comparable numbers of omitted site components. However, cognitive maps drawn by participants who observed the PM on physical model, exhibited greater spatial differentiation and detail. These maps more frequently included distinctions between settlement typologies, road hierarchies, and topographic features, resulting in higher overall evaluation scores.

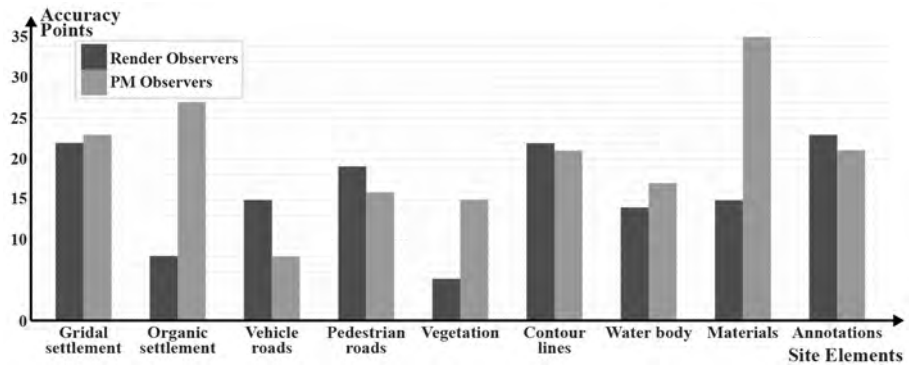

Fig. 5: Cognitive map results

In contrast, survey results revealed higher accuracy among participants who observed the digital rendering, particularly in questions requiring precise identification of zoning relationships and material characteristics. Participants observing PM on a physical model demonstrated slightly higher accuracy on questions about the quantitative aspects of site elements, such as relative sizes and proportions.

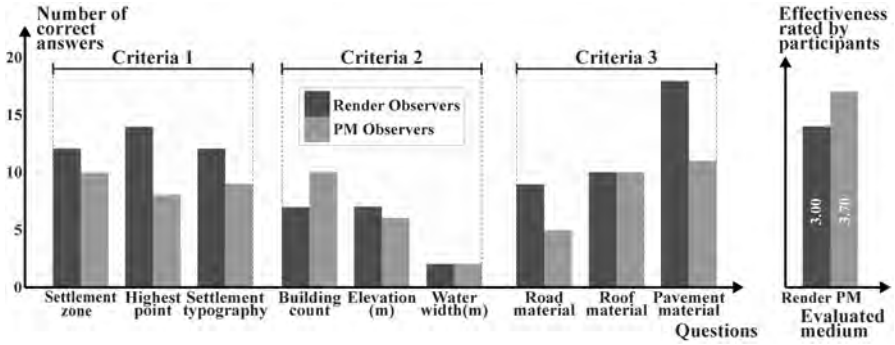

Fig. 6: Survey results in bar chart, categorized by the topic-based clusters (Criteria 1: general understanding of the spatial aspects and zoning, Criteria 2: quantitative aspects and numeric value ranges, Criteria 3: material perceptions)

Professional expertise and the corresponding range of spatial perspectives are critical factors when evaluating the efficacy of a new representational medium. Consequently, the results were cross-examined by experience level (categorized into students and educators) and further differentiated by the observed medium and evaluation method (Figure 7). The data indicates that students achieved higher scores in both survey accuracy and cognitive map precision when utilizing the projection-mapped physical model. Conversely, while educators demonstrated enhanced cognitive map accuracy with the PM medium, their performance on the survey component was lower when compared to their results using digital renderings.

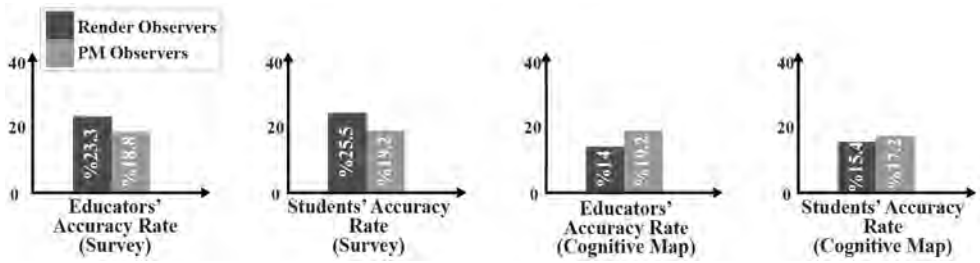

Fig. 7: Comparison between experience in the field (students vs educators) and accuracy based on use of different mediums (PM on a physical model vs render images)

Subjective evaluations by participants showed that PM was rated as more effective, while digital renderings were perceived as easier to understand. Analysis of written responses by

student participants suggests that unfamiliarity with PM contributed to initial confusion, despite participants expressing interest in the medium's potential. In addition, written responses by educators indicates this group of participants see potential in PM use and rate it as more understandable as well.

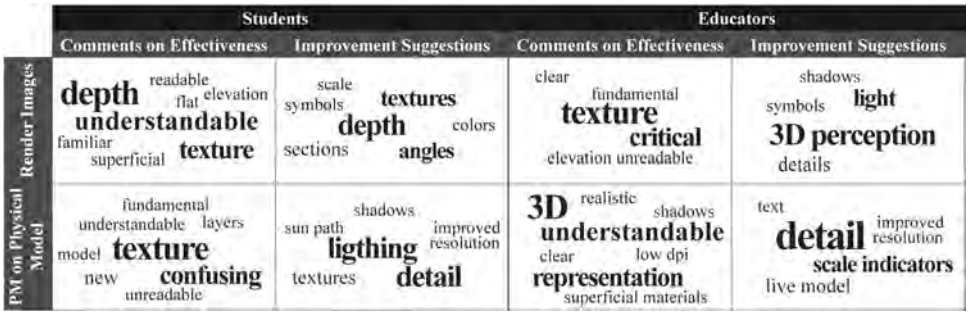

Fig. 8: Frequency wordcloud analysis of the written answers on comments on effectiveness and improvement suggestions, for both PM and render groups

These results indicate that PM and digital renderings support different cognitive processes: the former appears to enhance holistic spatial understanding, while the latter supports categorical and detail-specific recognition.

5 Discussion

The research demonstrates representational media uniquely shape cognitive processes in landscape architecture. While PM on physical models facilitates superior structural orientation and topographic recall, digital renderings excel in the recognition of other attributes such as zoning and materiality. Notably, the "situatedness" of the PM medium (MAHER & GERO 2002) effectively narrowed the performance gap between students and educators in spatial recall, validating the cognitive efficiency of physical engagement (PASSIG & EDEN 2000) in bridging the expert-novice divide. This suggests the materiality of the SAR-based model provides a foundational spatial clarity that benefits both novice and expert observers, moving beyond the surface-level engagement often associated with digital renders.

To ensure analytical rigor, the study utilized a two-phased cross-examination with both interpretive map analysis and quantifiable survey data. This approach embodies the "agency of mapping" (CORNER 1999), shifting the focus from the model as a static image to a process-oriented tool for systemic site discovery. While the evaluation of hand-drawn cognitive maps involves researcher interpretation, this qualitative method was strategically chosen to capture the multi-scalar spatial relationships that standard quantitative metrics often overlook. By employing this dual-phase evaluation, the study achieves a level of depth that provides a framework for identifying observable trends in emerging hybrid media, mitigating the risk of author-centered bias through expert-validated results.

The exploratory scope of forty participants was intentionally curated to facilitate a high-resolution, comparative study of expert versus novice cognition. The performance of the PM

group is particularly significant considering the participants' long-term fluency with industry-standard tools like SketchUp (GEORGE & SUMMERLIN 2019). That PM yielded such clear structural advantages despite the participants' established digital habits highlights its potential and resilience against digital bias. Practically, these results advocate for the integration of "Hybrid Design Mediums" in the design studio, where overlaying dynamic ecological or historical data onto physical models in real-time fosters a more immersive, process-oriented understanding. Future research should explore whether repeated exposure to PM further eliminates the initial learning curve, potentially establishing it as a primary tool for complex spatial evaluation.

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Evolution of GPUs and Virtual Landscape Design in Digital Games

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Abstract: This research examines how advances in graphics processing unit (GPU) performance affect the spatial and visual characteristics of virtual landscapes. Technological capacity shapes the range of aesthetic possibilities by limiting the kinds of visual detail, spatial complexity, and compositional control within a virtual landscape. A chronological dataset of all released NVIDIA GPUs has been compiled, including performance metrics: transistor count, VRAM capacity, floating-point throughput, texture rate, and pixel fill rate.

This dataset is aligned with a visual sample of Game of the Year (GOTY) award-winning titles. Screenshots from these games were systematically classified using a rule-based yes/no decision system derived from established landscape architecture eras (MANN 1993). Subsequently, a double-blind evaluation was conducted to ensure consistency across classifications. The analysis reveals GPU development emerges as a structural driver of stylistic change in virtual landscapes. Furthermore, the research provides a replicable methodological framework for linking computational capacity to aesthetic evolution in interactive environments.

Keywords: Virtual landscape, digital games, GPU evolution, landscape eras, landscape architecture

1 Introduction

The digital gaming industry has become one of the most technologically advanced and economically significant creative sectors since the late 20th century (RYKALA 2020). With each new generation of hardware reshaping the virtual landscape, visual and spatial possibilities change as well. By examining this process over time, this research offers a means of understanding aesthetic trends and future technological directions.

PEDDIE (2023) explains how Graphics Processing Unit (GPU) architecture has evolved, starting from fixed-function pipelines to programmable shaders and real-time ray tracing, enabling greater visual realism and new artistic styles in virtual landscapes. This connection between technology and aesthetics aligns with this researcher's aim of predicting future trends by establishing a system that analyses the historical evolution of the relationship between GPU advancements and trends in the virtual landscape.

The co-evolution of virtual landscapes with hardware performance, particularly the GPU, has not yet been systematically examined in the academic literature. This research addresses this gap by establishing a framework that links GPU performance indicators to the visual and spatial characteristics of virtual landscapes. The progression of landscape, art, and design movements throughout history demonstrates that technological innovations have continually reshaped how people perceive space and aesthetics, thereby influencing landscape architecture as a design discipline (MANN 1993).

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As virtual landscapes become a design medium rather than a derivative of physical space (VAEZ AFSHAR et al. 2022), they share fundamental experiential qualities with physical landscapes, allowing landscape architects to extend their disciplinary scope into virtual contexts (CORNER 1999). Understanding the relationship between artistic evolution and graphical computation is essential for predicting future design movements within the digital game landscape.

2 Reference Study

VAEZ AFSHAR, ESHAGHI, and KIM (2022) examined changes in the virtual landscape of gaming by analysing 702 educational games from 1992 to 2020. KIM's (2016) classification framework was used to track changes in scale, interactivity, and spatial structure over the years. Their results show that technological advances, particularly the development of virtual landscapes, have led to more complex, spatially rich game environments. This research explores how technology affects the visual and experiential aspects of design and provides insight into the development of a classification system, using games as a logical starting point. Our study examines how advancements in GPU drive the artistic evolution and visual complexity of virtual landscapes.

Art and landscape architecture have distinct eras corresponding to changes in their histories and disciplines (GAYNOR & MCLEAN 2005, SADIKHOVA 2024) and have influenced one another during each era. According to CORNER (1999), art inspires landscape architecture, with landscapes evolving through their representation in art and culture. This perspective established the connection between landscape art style eras and virtual landscape representations.

GIRÃO and SANTOS (2019) examined the historical interplay between art and technology, tracing how artistic innovation has continually evolved alongside scientific and industrial progress. Their research demonstrates that artistic experimentation has not only reflected technological change but has also actively driven it, establishing a cyclical relationship of mutual influence. This perspective offers a theoretical foundation for analysing the correspondence between successive artistic movements and technological revolutions, thereby informing the present research objective of linking GPU advancements to the stylistic evolution of virtual landscapes.

3 Methodology

The overall methodological process is structured as a sequential framework (Figure 1) which moves from measurable hardware constraints to perceptual outcomes. Establishing a relationship between computational capacity and spatial aesthetics.

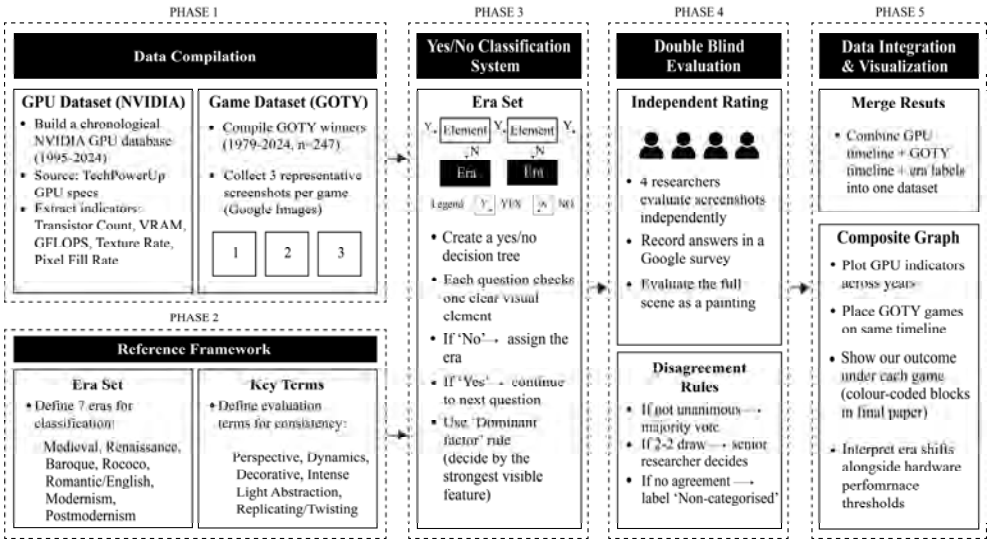

Fig. 1: Methodology Framework

The analysis begins with the construction of a chronological database of NVIDIA GPUs. NVIDIA was selected as the primary reference due to its long-standing dominance in the consumer graphics hardware market (PEDDIE 2023). Furthermore, since 1990, NVIDIA has consistently published detailed architectural data, offering a reliable technological timeline that documents the development of the hardware industry.

Performance indicator values such as transistor count, VRAM capacity, floating-point throughput, texture rate, and pixel fill rate were selected for each GPU model in the dataset. The transistor count reflects the overall computational capacity and the potential for advanced rendering architectures. VRAM capacity limits texture resolution and environmental complexity. Floating-point throughput indicates the computational power available for shader-based lighting and atmospheric calculations. Texture rate and pixel fill rate describe the efficiency of texture sampling and pixel rendering. Together, these values provide metrics for graphical capacity relevant to the development of virtual landscapes, such as light, texture resolution, and detail (KNEZ & NIEDENTHAL 2008, GUO et al. 2021) (Tables 1 and 2).

To relate this technological development to changes in visual representation, a collection of 247 Game of the Year (GOTY) award winners has been assembled, demonstrating the evolution of digital games and reflecting the state of virtual landscape representation at the time of each release. Game of the Year refers to titles selected annually by major award organisations, such as The Game Awards and the BAFTA Games Awards, for their outstanding artistic, technical, and design achievements in the gaming industry. (THE GAME AWARDS n.d., ARSENAULT 2009). While this subset of games may introduce selection bias, it aligns with the study's objective because of their high cultural visibility and technological ambition.

Table 1: GPU Dataset Compilation

Unit	Year	Product	GFLOPS	VRAM (MB)	Texture Rate (MTexel/s)	Transistor (million)	Pixel Fill Rat (GPixel/s
1	1995	NVIDIA NV1	0	2	150	1	0.0
2	1995	NVIDIA STG02000	0	1	150	1	0.0
3	1997	NVIDIA Riva 128	0	4	200	4	0.
		.					
		.					
		.					
1233	2026	GeForce RTX 5080 SUPER	56280	16384	879400	60000	33

Table 2: Performance indicators

Unit	GPU Performance Indicator	Primary Effect (Keywords)	Effect of Performance Growth (Keywords)
1	GFLOPS	Computational Throughput, Shaders	Realism, Complexity, Physics Simulation
2	VRAM(MB)	Texture Storage, Geometry data	Detail, Resolution, Scene Size
3	TEXTURE RATE (MTexel/s)	Surface Detail, Mapping Speed	Clarity, Sharpness, Richness
4	Pixel Fill Rate (Gpixel/s)	Rendering Speed, Frame Rate	Smoothness, Motion, Responsiveness
5	Transistor Count (million)	Architecture, Processing Power	Efficiency, Advanced Features, AI/Ray Tracing

To form a visual dataset for the subsequent classification, three screenshots of each game were collected from Google Images and cross-checked with official developer and publisher press kits. Collectively, these selections highlight the most widely recognised and representative visuals for each title. Furthermore, to connect the digital dimension of the research with the theoretical foundations of landscape architecture, two comparative sheets were prepared to illustrate the history of landscape architecture styles and the evolution of art movements (GAYNOR & MCLEAN 2005, SADIKHOVA 2024)

Building upon these foundations, a systematic approach was used to categorise the visual characteristics of the collected virtual landscapes. The categories, which correspond to the eras, were selected and refined based on the seven clearly identifiable eras: Medieval, Renaissance, Baroque, Rococo, Romanticism/English, Modernism, and Postmodernism. (MANN 1993). The number of eras was selected to capture the significant shifts in landscape representation while maintaining a limited number of categories to support consistent evaluation across images. Based on the described approach, a yes-or-no decision system was developed to classify each screenshot according to the characteristics associated with selecting the landscape movements. As shown in Figure 2, the system intentionally prioritizes dominant perception cues by reducing visual complexity, in line with principles of comparative judgement (THURSTONE 1927).

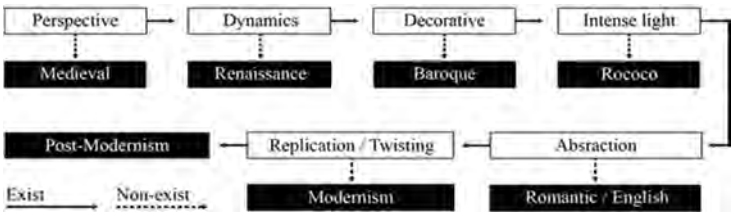

Fig. 2: Classification System

Each question isolates a single formal element. By determining the presence or absence of these visual attributes, the evaluator either identifies the corresponding stylistic movement or proceeds through the decision-making process. To ensure consistent interpretation across evaluators, a “Dominant factor” rule was introduced, based on comparative judgement principles, which indicate that humans are more reliable when decisions are made on the domi-

nance of a single attribute (THURSTONE 1927). Additionally, key terms used in the decision system were clearly defined as follows.

Perspective: The structure, defined by converging lines and scaling, creates a sense of three-dimensional depth.
Dynamics: The movement or directional force in a consistent spatial layout.
Decorative: The ornamental surface treatment.
Intense light: The dramatic use of contrast and radiance.
Abstraction: The simplification of natural forms into geometric expressions.
Replicating/Twisting: The recombination of different historic movements.

In accordance with these definitions, a double-blind process, adapted from CASCONE et al. (2023), is implemented. The evaluation process was conducted independently by four researchers: one senior academic with a PhD in landscape architecture and three undergraduate landscape architecture students. Without consulting one another, each researcher applied the Yes/No system to the set of screenshots and recorded their answers in a Google survey as an independent assessment across multiple sessions to mitigate the effects of reviewer fatigue. Each screenshot was evaluated as a complete visual composition, not limited to architectural elements. The evaluation included all visible components such as sky, vegetation, and atmospheric conditions. The images were examined in their entirety, using the same analytical approach applied to a painting, to ensure that the classification accurately reflected their overall spatial and visual qualities (RAAPHORST et al. 2017, 125-128). To improve the consistency of the decision-making process, works from historic landscapes were adopted. (e.g. Romantic Landscape Painting).

The recorded responses were compared once all evaluations were complete, with three rules established to resolve any disagreements. If the answers are not unanimous, firstly, we prioritise the majority vote. In the event of a draw (two to two), the senior researcher's judgment is prioritised. Finally, in the absence of agreement, the game will be classified as “non-categorised”. The collective results were combined into a single sheet, representing the agreed-upon classification outcome (Figure 3).

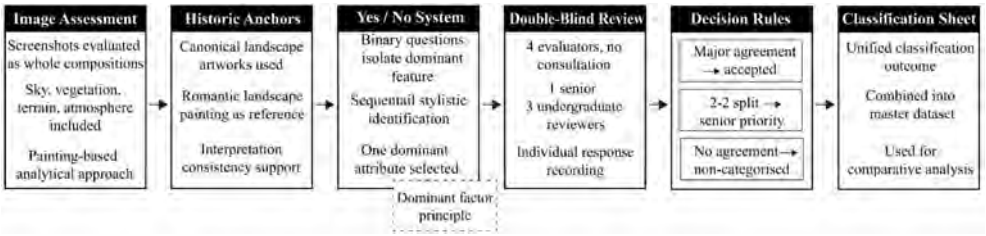

Fig. 3: Evaluation process framework

At this stage, a single composite graph was created using all collected datasets, including the GPU chronology, the GOTY games, and the corresponding assigned Landscape eras. In this graph, each performance indicator value was colour-coded and displayed throughout the years, while the associated game and its identified movement were positioned along the x-axis. This comparative visualisation illustrates which landscapes and Landscape movements dominated during specific hardware periods and how shifts in GPU architecture corresponded to transitions in spatial and stylistic approaches to virtual landscape design.

Finally, all GPU data, GOTY games, and classification results were brought together for comparative analysis. The GPU variables were plotted over time to track changes in performance. Each unit, such as VRAM, transistor count, or pixel rate, was first presented in separate graphs and then merged into a single chart, with colour coding used to distinguish them. GOTY games were placed along the same timeline, represented as blocks. The results of the double-blind classification were presented below each match, with blocks coloured to indicate the identified landscape era. This allowed visual tracking of how stylistic eras shifted alongside GPU performance. The combined dataset was then examined to identify instances in which hardware changes aligned with transitions in the virtual landscape, providing the basis for the results and discussion that follow.

4 Results

The research reveals a correspondence between advances in GPU technology and the evolution of landscape architecture aesthetics in video games. To validate the classification process, an inter-rater reliability test was conducted. The results yielded a Fleiss' kappa score of 0.719, indicating a "substantial agreement" among the raters. A majority (3/4) agreement was achieved in 87.35% (214 games), the unanimous agreement rate (4/4) was 59.59% (146 games). Only seven entries remained uncategorised due to atypical visual patterns, such as board games and visual novels, and could not be associated with any specific era. Each screenshot represents one classified example per Landscape era. Overall, these findings confirm that the methodology provides a successful system for analysing stylistic transitions in games (Figure 4).

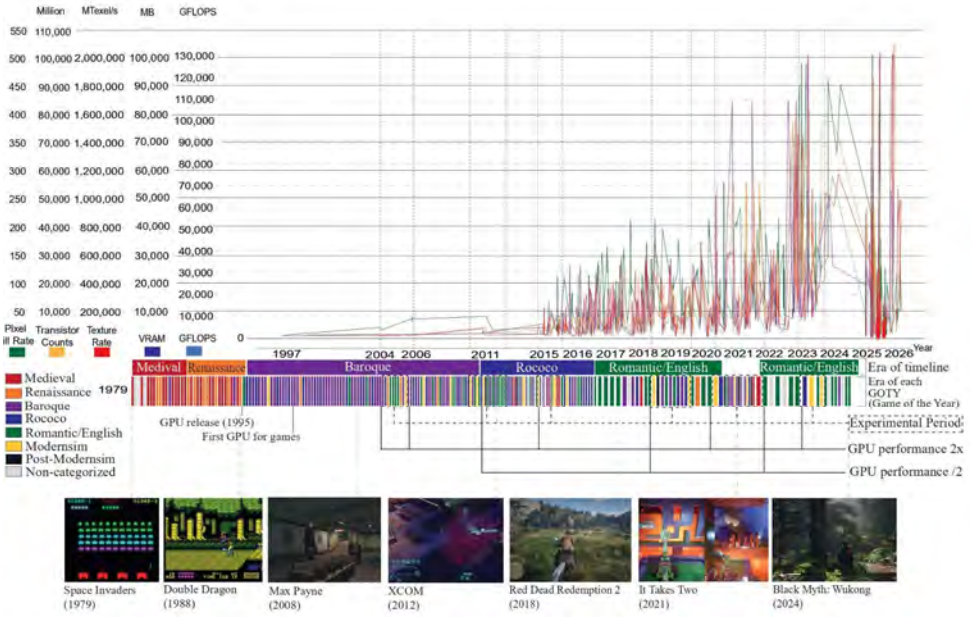

Fig. 4: Integrated Composite Graphic

As shown in Figure 4, the Medieval and Renaissance Periods are associated with the "Video Graphic Array" (VGA) standard and the limitations of early 2D accelerators. During the 1979-1996 period, a lack of hardware for "Transform and Lighting processes" (T&L) led to simplified geometric forms, with the virtual landscape serving as a tool for other domains rather than as an independent design purpose.

In 1997, with the first release of GPUs and hardware-accelerated T&L technology, the Baroque Period began and lasted until 2011. This period was driven by advances in computational power that enabled the generation of spatial arrangements and the control of movements. In 2009, the development of programmable shader units and the release of DirectX 11 technology raised the computational ceiling required for the dense ornamentation and visual complexity identified in Figure 4. Notably, the transition to the late Baroque Period and the emergence of the Rococo Period around 2010 were strongly influenced by the 569.1% GFLOPS ceilings observed between 2010 and 2015.

With the release of early versions of Real-time Ray Tracing in 2017, AI-driven rendering to create physically accurate light paths, and romantic visuals, the Romantic era aesthetics became more dominant in games. While the 2019-2023 growth phase recorded a 463.6% increase in GFLOPS, the dominance of the Romantic Period continued until 2021. The transition to hybrid "experimental visual systems" in 2022 showed a further 135.2% increase. The Romantic Period ends and the Experimental Period begins with the introduction of Mesh Shaders, which enable the technical power for more complex and non-traditional geometric structures, eventually breaking the period consistency. This period concludes the latest dominant period through rapid GPU shifts but delays the next one as developers explore technical and visual capabilities.

Finally, analysis of the 2023 technological peak revealed a significant performance disparity between flagship and mainstream hardware. A comparison of the GeForce RTX 4070 Ti (mainstream GPU) and the RTX 4090 (flagship GPU) reveals that mainstream cards offer less than half the performance of the 2023 consumer peak. This gap shows that "Romantic" era visuals or experimental period aesthetics are limited by mainstream hardware's capabilities. No further analysis was conducted to investigate the connection between development budgets and GFLOPS utilisation, as the study focused on the evolution of hardware and aesthetics.

5 Discussion

Previous research on virtual landscapes has mainly examined either technological advancements or artistic evolution (PEDDIE 2023, RAAPHORST 2017, VAEZ AFSHAR et al. 2022). In many of these studies, virtual landscapes are evaluated by the development of the art style. The present results contribute to the study of virtual landscape eras by showing that technological developments in GPUs influence changes across periods, with GPU performance acting as a structural enabler rather than a sole determining factor. Transitions between periods are frequently driven by GPU performance increasing or decreasing by at least a factor of 2 (Figure 4). Prior to major transitions, experimental periods are observed in the pattern shown in Figure 4. Experimental periods demonstrate how advances in GPU performance shape virtual landscapes by exploring various eras of landscape design. The pattern in Figure 4 indicates that periods dominated by a particular landscape era also contain early, scattered

appearances of subsequent eras, which then become dominant in the following phase. Based on the results, an increasing number of "non-categorised" GOTY titles and the latest experimental period foreshadow the modern period, which can be predicted for future virtual landscapes.

6 Conclusion

The research concludes that GPU performance growth is a determining factor in the characteristics of virtual landscapes. This growth is not merely a visual upgrade with improved textures and resolution; it is a defining feature of the graphic style. The results indicate a correspondence among GPU performance, visual characteristics, and the development of virtual landscape periods. These findings align with previous research emphasising the interconnection between technological investments and artistic styles in virtual landscapes. PEDDIE (2023) demonstrated that, throughout history, GPU advancements have enabled new creative styles and visual quality, while MANN (1993) argued that technological innovations have shaped human perception of space and aesthetics, which in turn have influenced landscape architecture movements. The present research extends this theoretical framework by providing a dataset demonstrating how GPU technology alters visual characteristics in virtual landscapes.

For landscape architecture, these results are relevant for predicting future periods within virtual landscapes. Understanding how technological innovations affect the visual characteristics and human perception of landscapes is essential for landscape architects to engage with virtual landscapes and forecast aesthetic periods. This research demonstrates that GPU technology is a significant factor in virtual landscapes and offers future insights for landscape architects and designers.

However, this study is limited since GFLOPS is the primary measure of hardware performance, overlooking memory bandwidth, architectural efficiency, and software optimisations such as DLSS. Future research could address this limitation by measuring both AI-assisted software and the efficiency of hardware architecture. Additionally, the scope of this study is limited to PC GPU architecture, as the data is based specifically on the NVIDIA GPU database, overlooking any AMD and console-specific hardware. Future studies could expand this dataset to include different hardware ecosystems, providing a more comprehensive comparison of the influence on landscape aesthetics. Also, the dataset prioritises mainstream-awarded games over indie games with distinctive design choices. Finally, while technology and digital art style trends progress together, other factors, such as player trends and market changes, cannot be ignored, shaping the state of virtual landscapes in games.

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Comparison of Traditional (2D) and Stereoscopic (3D) Flood Visualization in supporting Flood Risk Assessment

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Abstract: Stereoscopic 3D visualization expands flood risk assessment by adding depth and realism to the way hydrologic model results are displayed. This study explores the benefits of using stereoscopic 3D visualization in comparison to traditional 2D flood visualization methods to support flood risk assessment. A quasi-experimental approach was used to rate the helpfulness of using 2D and stereoscopic 3D visualizations to answer nine flood risk assessment questions. The results show that both 2D and stereoscopic 3D visualization are effective though sometimes complimentary with each approach having different strengths and weaknesses. Questions of assessing safety showed the greatest differences with 2D maps rated as unhelpful and stereoscopic 3D visualizations rated as helpful. Conclusions suggest that stereoscopic 3D flood visualizations are effective and will likely become more available as 3D modeling technology improves. They also suggest that more research is needed to explore the benefits of stereoscopic 3D flood visualizations for flood risk assessment and for expanding flood risk awareness to more stakeholders in the community.

Keywords: Flood risk, virtual reality, hydrologic modeling, visualization

1 Introduction

Flood visualization has long been an effective motivator at the policy level and is used by advocates of change (FEMA 2022, NOAA 2025). However, while federal, state and local agencies offer mapping visualization of river flooding and sea-level rise, the format of these 2D mapping applications may not be sufficient to fully communicate flood risk to untrained community stakeholders (ZHU et al. 2025, DE SANTIS et al. 2019, RAUTENBACH et al. 2017). Previous studies have called for empirical studies to assess how stereoscopic 3D visualizations affect risk perceptions (KUSTER et al. 2023, SIMPSON et al. 2022, CHARRIERE et al., 2012). Stereoscopic 3D visualization is a game changer in its ability to visualize flooding solutions at human scale as though you are actually present at the scene during the flood (BAKHTIARI et al. 2023). Immersed in their virtual neighborhood, decisionmakers can view 3D flood simulations to better assess flood risk.

This study is a quasi-experiment involving stakeholder participation to determine the acceptance and effectiveness of using stereoscopic 3D visualization to assess pluvial flooding vulnerability. It explores whether public officials and community organizers find stereoscopic 3D visualization as an effective way to visualize flooding and assess flood risks? It also looks at the differences between stereoscopic 3D visualizations and traditional plan, elevation and tabular representations of model results.

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2 Methods

2.1 Flood Scenario Generation

Flooding scenarios in this study are pluvial, representing urban surface water floods caused when stormwater exceeds the capacity of the infrastructure. Older urban neighborhoods such as those in Baltimore, MD are at high risk to pluvial flooding due to a lack of protection. The study area is located at the corner of East Lafayette Ave and North Castle Street in Baltimore, MD. The spatial data used to produce the scenarios was obtained through Open Baltimore (https://data.baltimorecity.gov/) including 2-foot contours, building footprints, edge of pavement, vegetation, soils, aerial photos, stormwater pipe network, property lines, etc. On-site surveys were conducted to verify and update all data. ArcGIS Pro was used to process the data for defining the watershed boundary, populating the WinTR-55 hydrologic model for small watersheds, and running a Hazen-Williams pipe flow model. AutoCAD and SketchUp were used to establish the floodplain cross-sections and flood surfaces. Sketchup and Lumion were used to build and render the 3D model, and Lumion was used to produce the 2D and stereoscopic 3D visualizations. Photoshop was used to optimize the color and contrast for viewing on Meta Quest 3S VR headsets. Pigasus VR Media Player was used to view all visualizations in the VR headset.

2.2 Sample Population

Participants were recruited using a convenience sample approach to include a balanced mix of users. These include community leaders, public agency professionals, private sector professionals, and community residents. Recruitment included direct email, flyers at targeted professional events, and tabling at community events. Participants were given boxed lunches to compensate for their time.

2.3 Training and Flood Risk Assessment

All participants were trained to use the VR headset to view visualizations prior to completing the flood risk assessment experiment. Visualizations (Figure 1) included a table of hydrologic model results, a 2D plan view of a flooded intersection, a 2D elevation of the intersection, a stereoscopic 3D 360-degree eye-level visualization of the intersection, and a stereoscopic 3D 360-degree aerial view. The flood scenario was a 10-year return period. Nine flood risk assessment questions are presented in section 3.2.

Each of the nine questions required the following tasks, 1) use the headset and five visualizations to answer the question, and 2) rate each of the five visualizations in how helpful they were in answering the question. Each rating question had a choice from one to seven where 1 equaled “not helpful”, and 7 equaled “very helpful”.

TR-55 Table

FLOW RATES

Storm Period	TOTAL PEAK FLOW		
1-yr	Peak Flow Rate	ft³/s	536
10-yr	Peak Flow Rate	ft³/s	1281
25-yr	Peak Flow Rate	ft³/s	1400
100-yr	Peak Flow Rate	ft³/s	1869

	CHANNEL FLOW		
	Velocity	f/s	3.45

Manning's n	UNDERGROUND PIPE FLOW (Full)		
0.018	Flow Rate, Qf	ft³/s	659
0.025	Flow Rate, Qf	ft³/s	474
Hazen-Williams C			
90	Flow Discharge	ft³/s	738
100	Flow Discharge	ft³/s	819

SURFACE PEAK FLOW (ft³/s)
flow minus Pipe flow (Brick & Stone)

	TR-55 - MANNINGS		TR55 - HAZEN/WILLIAMS	
	0.018	0.025	90	100
1-yr	-123	62	-202	-283
10-yr	622	807	543	462
25-yr	741	926	662	581
100-yr	1210	1395	1131	1050

PIPE DIAMETER
8 ft (96 in)

PIPE SLOPE (estimated)
13 Elevation Change ft (North/Chester. to Washington/Lanvale)
1325 Pipe Distance ft
0.00981 Slope

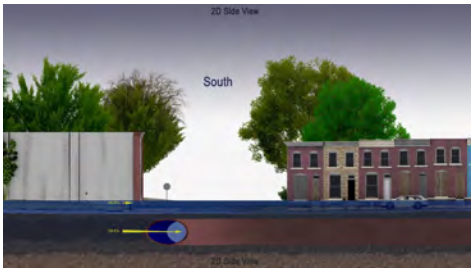
HAZEN-WILLIAMS C - Brick Sewer
90-100

MANNING'S n - Brick/Stone
.015-.025

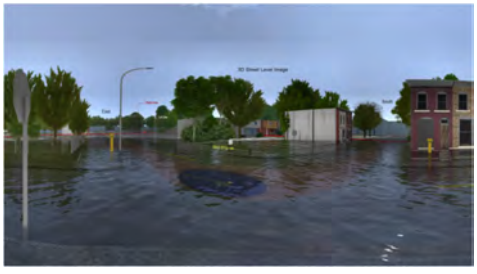
TR-55 Table

Table

2D Map



2D Elevation



3D 360° Eye-Level View (cropped)

3D 360° Aerial-Level View (cropped)

Fig. 1: Above are the five visualizations that participants viewed in VR headsets to answer flood risk assessment questions. Only the 3D 360-degree visualizations were stereoscopic and fully immersive. All visualizations were viewed within the VR headset. The table and 2D visualizations appeared to participants as if it was an eye-max theatre experience (2D but full screen). The stereoscopic 3D 360-degree views were cropped here for viewing in a standard publication format.

3 Results

3.1 Participant Characteristics

A total of 52 people participated in our study. Mean age was 51.12(SD: 18.07) years old. Forty-five percent of participants were male while fifty-five percent were female. Fifty-eight percent of participants were white, twenty-seven percent were black, eight percent Asian, two percent American Indian or Alaskan native, and six percent other. Eight percent were Hispanic and ninety-two percent non-Hispanic.

3.2 Repeated Measures ANOVA and Pairwise Comparison

The results presented here include the comparison of ratings for each visualization for each of the nine flood risk assessment questions. Preliminary analyses were completed using Repeated Measures Anova. Mauchly's Test of Sphericity (that the variances of the differences between all pairs of groups are equal) was significant for all nine questions, so Greenhouse-Geisser correction was used to test for within-subjects effects. The Greenhouse-Geisser results were significant for all questions indicating that significant differences exist among the visualization ratings for each flood assessment question. Finally, a post-hoc pairwise comparison was completed to determine how each visualization was rated relative to other visualizations. Bonferroni correction was applied. The error bars in the charts below, though technically not correct for within-subjects testing (CUMMING et al. 2007), do offer a good visual approximation of significant differences.

Each graph shows the rating on the Y axis ("not helpful" to "very helpful") and the visualization type on the X axis. The value of 4 was highlighted in red as a neutral value neither very helpful nor not helpful. The graphed points represent the mean value for all observations. The range lines for each mean represents the 95-percentile value.

Question 1: How many vacant lots in the area will be affected by the 10-year flood? (answer: 24, mean: 24.43, SD: 9.975) The ratings (Figure 2) of helpfulness on vacant lots' flood assessment among five visualizations were statistically significant ($F(2.98, 146.23) = 37.07$, $p < .001$, partial $\eta^2 = .65$). Here the "2D Map" and the "3D Aerial" were rated the most helpful while the "Table", "2D elevation" and "3D Eye-Level" were considered less helpful (below the neutral value of 4).

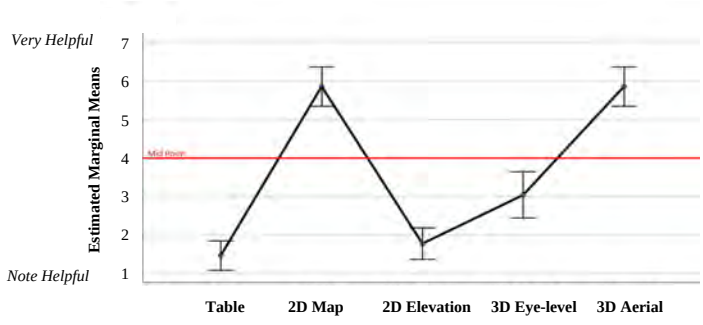


Fig. 2: Graph of estimated marginal means for question 1

Question 2: How many row houses in the area will likely have flood water entering the building? (answer: 15, mean: 18.16, SD: 7.347) The ratings (Figure 3) of helpfulness on row houses' flood assessment among five visualizations were statistically significant (F (2.72, 127,87) = 45.14, $p < .001$, partial $\eta^2 = .49$). Here the "2D Map", the "3D Eye-Level" and the "3D Aerial" were rated the most helpful while the "Table", and "2D Elevation" were considered less helpful.

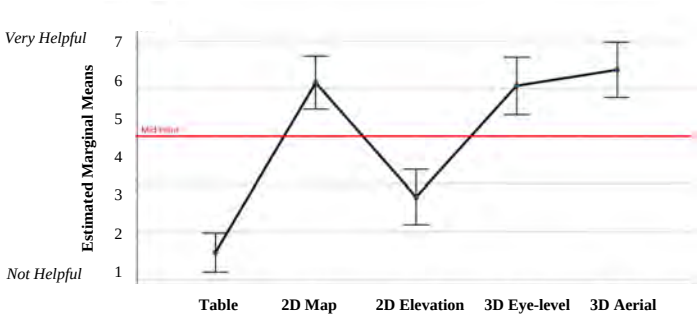


Fig. 3: Graph of estimated marginal means for question 2

Question 3: How safe is it to walk through the flooded intersection during the 10-year flood? (1=not safe to 7=very safe, mean: 1.83, SD: 1.41) The ratings (Figure 4) of helpfulness on walking safety among five visualizations were statistically significant (F (3.55, 170.14) = 57.45, $p < .001$, partial $\eta^2 = .55$). Here the "3D Eye-Level" was rated the most helpful while the "Table" and "2D Map", were considered less helpful. The "2D Elevation" and the "3D Aerial" were neither very helpful nor not helpful.

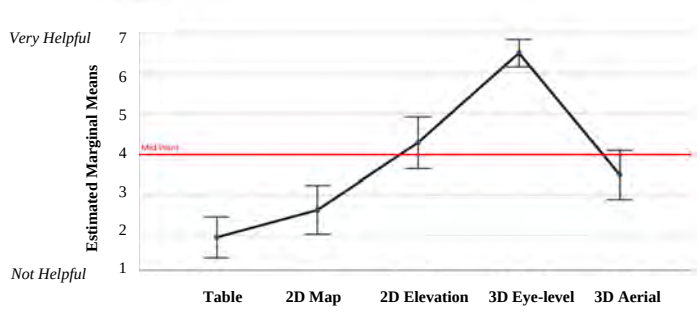


Fig. 4: Graph of estimated marginal means for question 3

Question 4: How safe is it to drive through this intersection during the 10-year flood? (1=not safe to 7=very safe, mean: 1.29, SD: 0.92) The ratings (Figure 5) of helpfulness on drive safety among five visualizations were statistically significant (F (3.18, 149.23) = 53.03, $p < .001$, partial $\eta^2 = .84$). Here the "2D Elevation" and the "3D Eye-level" were rated the most helpful while the "Table" and "2D Map" were considered less helpful. The "3D Aerial" was neither very helpful nor not helpful.

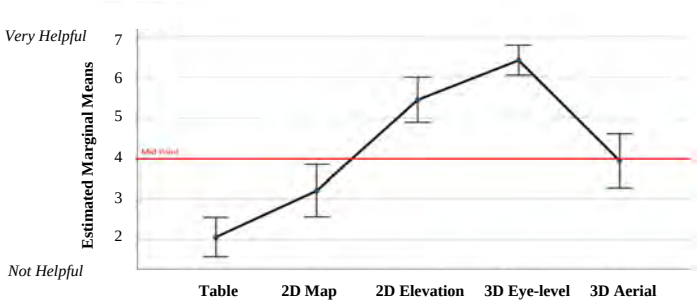


Fig. 5: Graph of estimated marginal means for question 4

Question 5: Which direction is the flood water flowing? (**From**: north 55.8%, east 25%, other 5.8% or less, **To**: south 55.8%, west 25%, other 3.8% or less) The ratings (Figure 6) of helpfulness on the flood water direction among five visualizations were statistically significant ($F(2.72, 133.03) = 19.76$, $p < .001$, partial $\eta^2 = .83$). Here the "2D Map" was rated the most helpful while the "Table" and "2D Elevation" were considered less helpful. The "3D Eye-Level" and the "3D Aerial" were neither very helpful nor not helpful.

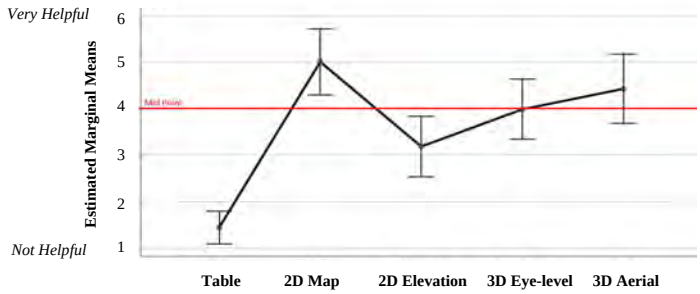


Fig. 6: Graph of estimated marginal means for question 5

Question 6: How fast is the surface water flowing in ft³/s? (answer: 543 ft³/s, mean: 586.83 ft³/s, SD: 223.736) The ratings (Figure 7) of helpfulness on the surface water speed among five visualizations were statistically significant ($F(3.42, 167.57) = 27.84$, $p < .001$, partial $\eta^2 = .72$). Here the "Table", the "2D Elevation", and the "3D Eye-level" were rated the most helpful while the "2D Map" was considered less helpful. The "3D Aerial" was neither very helpful nor not helpful.

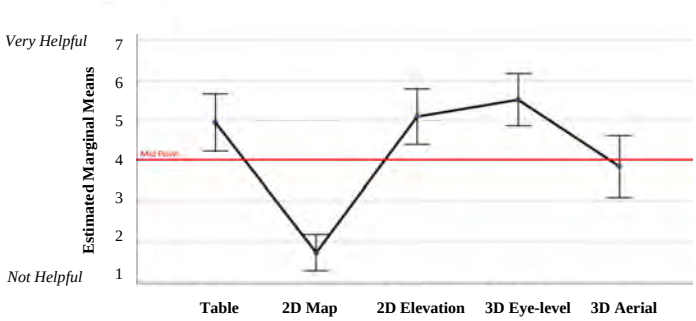


Fig. 7: Graph of estimated marginal means for question 6

Question 7: How would you rate the flood risk at this intersection? (1=no risk to 7=very high risk, mean: 6.51, SD: 0.81) The ratings (Figure 8) of helpfulness on the flood risk among five visualizations were statistically significant (F (3.18, 155.93) = 15.78, $p < .001$, partial η^2 = .57). Here the "2D Elevation", the "3D Eye-Level" and the "3D Aerial" were rated the most helpful while the "Table" and the "2D Map" were neither very helpful nor not helpful.

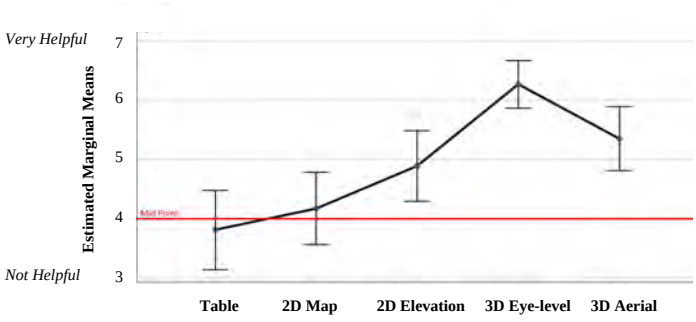


Fig. 8: Graph of estimated marginal means for question 7

Question 8: How extensive is the flood risk in this neighborhood? (1=no risk to 7=very high risk, mean: 5.73, SD: 1.22) The ratings (Figure 9) of helpfulness on the flood risk extensiveness among five visualizations were statistically significant (F (2.96, 142.01) = 21.39, $p < .001$, partial η^2 = .31). Here the "2D Map", the "3D Eye-Level" and the "3D Aerial" were rated the most helpful while the "Table" was considered less helpful. The "2D Elevation" was neither very helpful nor not helpful.

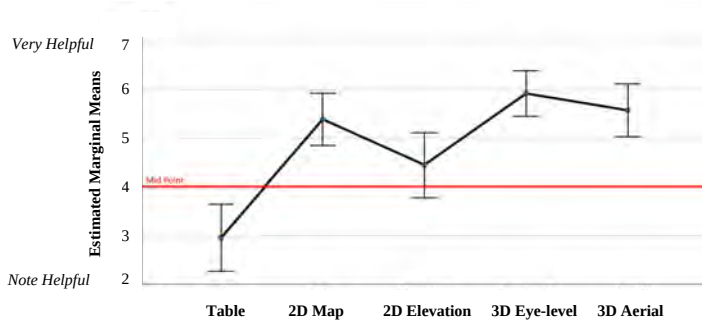


Fig. 9: Graph of estimated marginal means for question 8

Question 9: Overall, how helpful are the following visualizations for assessing flood risk? The ratings (Figure 10) of helpfulness on overall flood risk among five visualizations were statistically significant (F (2.98, 146.23) = 37.0, $p < .001$, partial $\eta^2 = .65$). Here the "2D Map", the "2D Elevation", the "3D Eye-level" and the "3D Aerial" were rated the most helpful while the "Table" was neither very helpful nor not helpful.

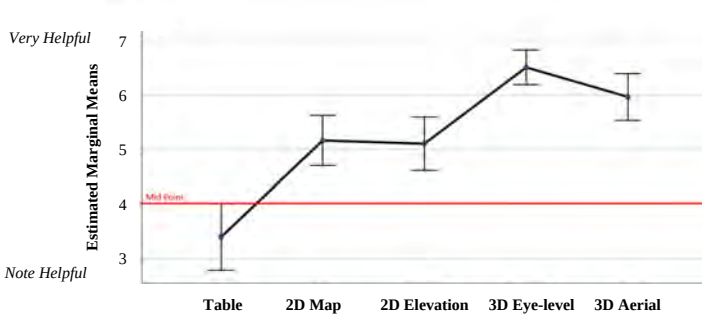


Fig. 10: Graph of estimated marginal means for question 9

Summary Table of Helpfulness: The sum of all questions (Figure 11) that reported a positive value for helpfulness (95 percentile above the estimated marginal means of 4) are shown in the bar graph. Here the "Table" positively supported only one of the risk assessment questions. The "2D map" and "3D Aerial" each supported five questions. The "2D Elevation" supported four questions. And the "3D Eye-level" positively supported seven questions.

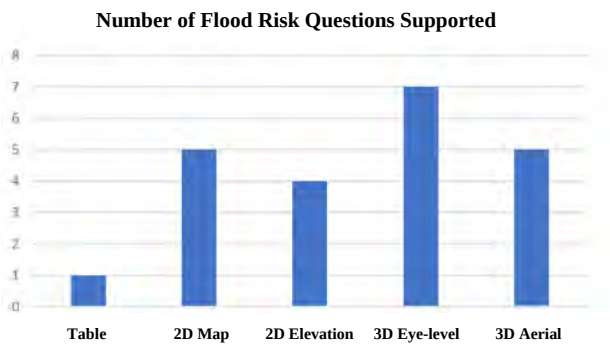


Fig. 11: Number of flood risk questions supported for each visualization

4 Discussion

Two of the key advantages of stereoscopic 3D visualization over 2D maps include depth and realism. People do not experience the world in 2D and so 3D visualizations offer a view of the world that is more compatible with people's everyday experiences. Experiencing flood modeling in stereoscopic 3D has the potential to map onto people's understanding of flood risks with levels of complexity that can only be achieved with depth and realism. The benefits are still largely unknown and should be explored in greater depth. Traditional 2D visualizations have the advantage of simplicity through abstraction. They have been used for flood risk assessment for years with measurable success. The questions are, how much more could be learned about flood risk by expanding flood visualization into three dimensions? How many more people can be included in the decision-making process by making the data more relatable to everyday experiences of the world? How many lives can be saved and how much property can be protected by expanding flood risk assessment capabilities and by communicating flood risk to a greater proportion of affected communities? Current technologies now make it possible to view hydrologic modeling in three dimensions and this study provides evidence that significant benefits exist to using them.

Strengths, weaknesses, and differences between traditional 2D and stereoscopic 3D visualizations were shown to exist. First, with respect to stereoscopic 3D visualizations, these were shown to display modeled flood data in ways that effectively communicate flood risks for flood risk assessment. The "3D Eye-Level" visualization rated highest overall for helpfulness in assessing flood risk but fell short in neighborhood level questions (1, 2, and 8) that required an overall view of the study area. The "3D Aerial" rated high in neighborhood level assessments and overall risk extent but fell short in flood flow and personal safety questions that may be better supported from views closer to the ground. Second, traditional visualizations are also helpful for assessing flood risk. The "2D Map" rated high in neighborhood level assessments and overall risk extent questions but fell short in technical flood flow and personal safety questions. The lack of support for personal safety questions is an important finding because 2D maps are currently the primary visualization technique for flood risk assessment. The "2D Elevation" ratings were mixed for safety and flood flow questions and fell short in neighborhood level questions. Still, it rated high for helpfulness overall. Finally, the

data “Table” rated high for flood flow speed, but fell short in neighborhood level assessments, safety assessments, and flood direction. Overall, it did not rate as being useful. Still, all the visualizations were produced using the table information, and hydrologic modelling technicians would likely be skeptical of the visualizations without having it available.

Limitations to this study include a lack of causal information, sampling bias and generalizability, adoption of VR, and modelling costs. First, the results do not provide information as to why participants rated the different visualizations. Knowing the causal relationships would better guide future development. While the causal reasons are not yet clear, we believe the results of this study provide a compelling argument for continued development in this area of visualization. Second, although the sampling approach ensured some level of relevance to likely users of the technology, it is also susceptible to researcher bias. To expand to a larger audience, future sampling should be guided less by convenience and more by generalizability. Third, adoption of VR by municipalities has been slow. Like cell phones of the 1970s, VR headsets can be bulky and costly. Advancements in wireless connections, higher resolution, reductions in cost, etc. continue to bring down barriers to widespread adoption. Research like the study presented here has always been ahead of the market and is critical for further advancement. Meta and Apple are both producing consumer grade VR products and applications. There is reason to be optimistic that widespread adoption throughout government and communities is on the horizon. Finally, it currently takes time and effort (costs) to produce stereoscopic 3D visualizations. However, advancements in producing and rendering highly realistic stereoscopic 3D models efficiently continue at an accelerated rate through drone-based LiDAR scanning and photogrammetry. The costs for producing 3D models are likely to come down in the future, and thus the demand and availability will likely go up.

Future research might build on this study in several ways. First, the visualizations might be expanded to include a range of design solutions. Thus, assessments would build upon existing conditions (this study) by adding visualizations and assessments of future alternative conditions. Second, future studies might include looking at combinations of different visualization types, e.g. stereoscopic 3D visualizations and tables, and to assess the combined effectiveness for answering different types of flood risk assessment questions. The results of this study suggest that combined effectiveness is likely to exist and could be important for guiding infrastructure investments. Finally, a closer look at how different user groups or stakeholders respond to the different visualization techniques would be helpful. Hydrologic modelers may look for different types of information than city council members or community residents. Understanding which visualization techniques best answer typical risk assessment questions, and how each stakeholder group benefits from using the visualization techniques will help guide further development and deployment of them.

5 Conclusion

Together, traditional 2D flood visualizations and stereoscopic 3D visualizations were considered helpful overall in supporting flood risk assessment but with different strengths for each. Stereoscopic 3D visualizations were slightly more supportive overall than 2D traditional visualizations. The 2D map, which is by far the most common flood visualization technique, failed to support assessments of safety to walk or drive through a flooded intersection

while stereoscopic 3D visualizations were found to be more supportive. Tabular data provided minimal support for flood risk assessment with respect to the questions used in this study. Nonetheless, all sources of information – tabular, 2D visualizations, and stereoscopic 3D visualizations – provided at least some level of support for answering questions related to flood risk assessment.

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Exploring the Application of Mobile VR Immersive Gallery Across Multiple Scenarios and Uses in Design Activities

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Abstract: This study aims to explore the use of a mobile Virtual Reality (VR) immersive gallery across multiple scenarios in design activities. The research team develop a mobile VR immersive gallery which serves as a fundamental framework for specific functions for design education, professional design practice, design engagement, and various design activities. The gallery can be deployed in any 6 m × 6 m indoor or outdoor space using wireless VR headsets, allowing multiple users to freely explore design content without spatial or temporal limitations. To investigate its applications, the research team further develop the VR gallery to meet the requirements of three design scenarios: a final review of a landscape design studio at Arizona State University, a stakeholder presentation of a residential landscape project in Shenzhen, and a design firm's introduction at an industry expo at Tongji University. Finally, in-depth interviews with 20 randomly recruited participants from all three scenarios are conducted to examine people's perceptions, experiences, and evaluations of this mobile VR environment. Results show that this mobile VR gallery enhances spatial understanding, engagement, and communication across settings, demonstrating its potential as a flexible visualization tool for multiple forms of design activities.

Keywords: VR technologies, immersive visualization, design communication, design education, design engagement

1 Introduction

1.1 Background

Immersive technologies such as VR enables a more realistic, immersive, and interactive visualization in various fields of design and supports better design communication (ALIZADEHSALEHI et al. 2019). FAROOQ et al. (2018) report that VR facilitates green street design by allowing stakeholders to experience simulated environments in an immersive way, thereby increasing spatial understanding and consistency (GE et al. 2023). HOU (2020) find a reduction of design iteration time by 40% and a 25% improvement in landscape design when immersive technologies are integrated. Some studies report that VR enhances both designers and stakeholders' perception of design details and make them more engaged through the entire process of sustainable landscape design projects (GE 2025). Meanwhile, immersive visualization with multisensory features (such as sound and temperature) can further enhance the positive effects on design communication and engagement (LOVIISA et al. 2023, MEENAR & KITSON 2020). Overall, multiple forms of VR visualization tools and related technologies have been developed and tested to support various design activities in landscape architecture and other design-related fields. Real-time VR rendering, immersive showrooms with panoramic screens, and VR animations featuring customized movable platforms have become

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popular directions in current research and development (DU et al. 2016, EDLER et al. 2019, RAHIMIAN & IBRAHIM 2011).

1.2 Challenge and Significance

Although many types of VR visualization tools have been developed and implemented in the design field, few teams have created a mobile VR immersive visualization system that offers a flexible and simple operation experience, high adaptability to different site sizes and conditions, a unique gallery mode, and the ability to quickly adjust content based on purpose. Therefore, the VR tool developed in this study represents a breakthrough within existing research.

Moreover, while various VR visualization tools are available on the market, evaluation and user studies specifically focusing on these tools remain limited. This study not only develops a mobile VR immersive gallery but also conducts preliminary assessments across three different scenarios and purposes. These evaluations effectively test the feasibility and application potential of such VR tools in multiple design activities. From the perspectives of landscape architecture practice and education, this research serves as an important attempt to use VR technologies to connect and benefit multiple design disciplines.

1.3 Research Questions

Based on the knowledge gaps and research goals, there are two research questions that need to be addressed in this study:

Question 1: How does a mobile VR immersive gallery influence participants' spatial understanding, engagement, and design communication across different design scenarios, including design education, design practice, and public exhibition?

Question 2: In what ways do users' perceptions, experiences, and evaluations of a mobile VR immersive gallery vary across different contexts of use?

2 Methodology

2.1 Research Design

In this study, the research team develops a mobile VR immersive landscape design gallery that can be set up in any 6 m × 6 m indoor or outdoor space using wireless VR headsets. This immersive environment allows multiple users to freely explore the gallery without time limits or a fixed sequence of scenes. The modeling and rendering workflows for this VR system were developed using Rhino, Blender, Unreal Engine, and Unity, with custom scripting implemented in Python where necessary. The immersive gallery was experienced through the PICO 4 Ultra Enterprise VR headset.

The VR immersive gallery serves various purposes, such as immersive reviews for landscape design studios, project presentations for professional firms, and exhibition spaces for workshops in landscape research and practice. People can just simply have the posters, models, and installations displayed within the VR environment to meet different objectives and user

needs. Figure 1 shows an example of the VR gallery used as a mobile art museum (example of one use of this VR immersive gallery, not employed in this study).

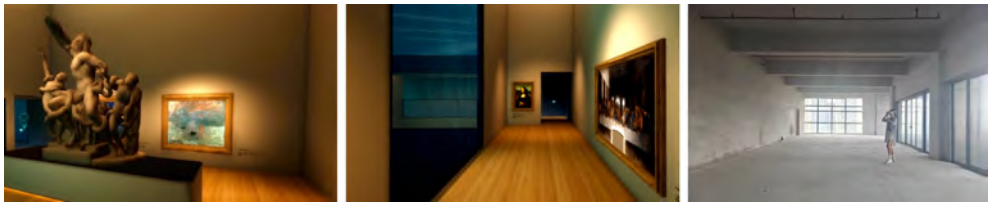

Fig. 1: Art museum created by the mobile VR immersive gallery

With the basic setup of the mobile VR immersive gallery completed, the research team proceeded to investigate its impacts across three distinct scenarios: (1) a final review for a landscape architecture design studio; (2) the presentation of an exhibition space design developed by a professional firm in collaboration with independent artists; and (3) the introduction of a design firm at an industry expo.

Scenario 1

For the first scenario, this study examines a third-year master's-level landscape architecture design studio at Arizona State University (ASU), taught during the Fall 2025 semester, as a case study. The mobile VR immersive gallery was employed as the primary medium for presenting students' final design work, including posters, digital models, and rendered scenes, within an immersive virtual environment. The VR gallery was utilized during the final review, enabling faculty members and external critics to engage with and evaluate student projects in a spatially interactive manner. The physical setup supporting the VR exhibition was located on the second floor of the UGB building at ASU.

Scenario 2

For the second scenario, the research team collaborates with a partner design firm in Shenzhen, employing the VR gallery as a platform to present collaborative exhibition space design work developed with independent artists to visitors at the Shenzhen–Hong Kong Bi-City Biennale of Urbanism/Architecture in December 2025. All design outcomes are exhibited within a shared virtual environment, allowing audiences to experience the projects in an immersive and spatially coherent manner. The VR presentation is situated within an unused and unfinished office space, a deliberately selected venue by the Biennale organizers, reflecting the exhibition's emphasis on adaptive reuse and experimental spatial conditions.

Scenario 3

Scenario 3 focuses on the introduction of design firms at an industry expo (the CADE Architecture Design Expo), the research team worked with a collaborated design technology firm and an architecture firm and employed the VR immersive gallery as a virtual firm profile. The VR gallery was presented at an industry expo held at Tongji University in Shanghai in November 2025 and was open to attendees from a wide range of professional and academic backgrounds. The installation was located in the main exhibition hall of the expo, allowing for high visibility and accessibility.

2.2 Interview and Data Analysis

After utilizing this mobile VR immersive gallery for different purposes across multiple settings, the research team randomly recruits participants who experience the tool to conduct in-depth interviews. Five participants from the studio review, five from the exhibition space design presentation, and ten from the industry expo take part in this study. Five interview questions (Table 1) which aim to investigate participants' perception and cognition of the VR gallery content, their subjective feelings during the immersive experience, their evaluation of this innovative tool, and their expectations for its future development are developed (To support the validity of analysis with a small sample size, the same interview protocol was applied across all three scenarios. Participants could provide scenario-specific feedback when responding to the shared set of questions).

Table 1: The design of interview questions

Interview Questions	**Question 1**	**Question 2**	**Question 3**	**Question 4**	**Question 5**
Aims	The General Experience	Comparative Visualization (3D Immersion vs. Traditional)	Critical Evaluation (Benefits & Shortcomings)	Impact on the Specific Design Scenario	Outlooks and Any Other Feedback

All interview responses are recorded, transcribed, and coded for thematic studies through NVivo14 to examine the potential impacts of this mobile VR immersive gallery across multiple scenarios and uses in design activities.

3 Results and Discussion

3.1 VR Immersive Gallery Outputs for Three Scenarios

For all three design scenarios, Figures 2 to Figure 9 present the spatial design concepts of the immersive VR gallery, representative views captured within the VR headset, and photographs documenting the on-site deployment and user interactions. Together, these figures illustrate both the virtual spatial configuration and the physical setup of the mobile VR immersive gallery across different contexts.

Scenario 1

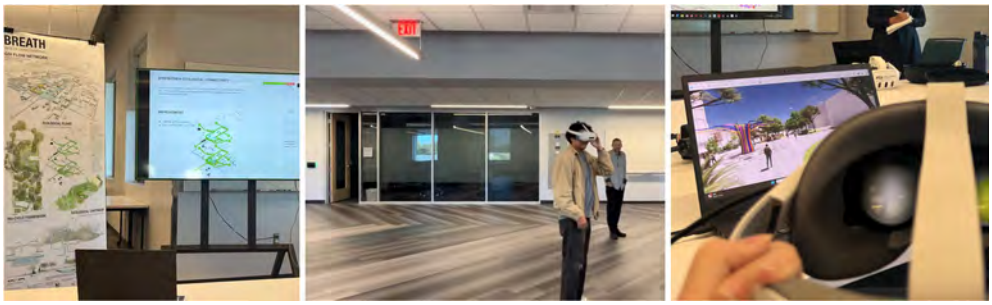

Fig. 2: Photos of the studio final review

Fig. 3: Recorded VR scenes

Scenario 2

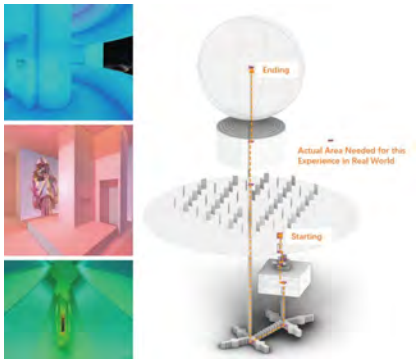

Fig. 4: VR space design concept

Fig. 5: Photos of the design exhibition

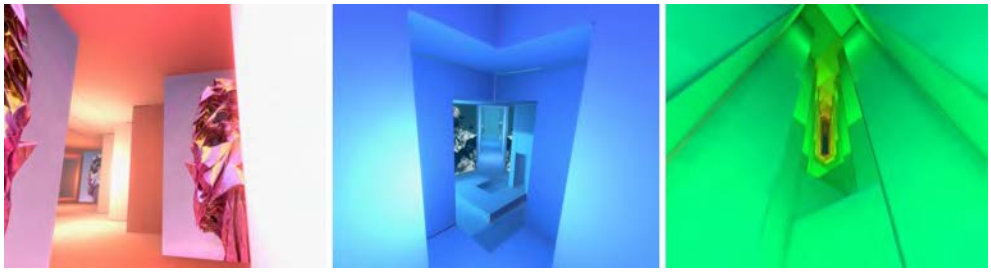

Fig. 6: Recorded VR scenes

Scenario 3

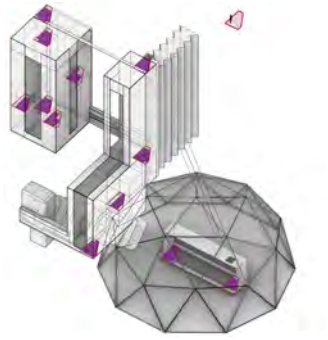

Fig. 7: VR space design concept

Fig. 8: Photos of the industry expo

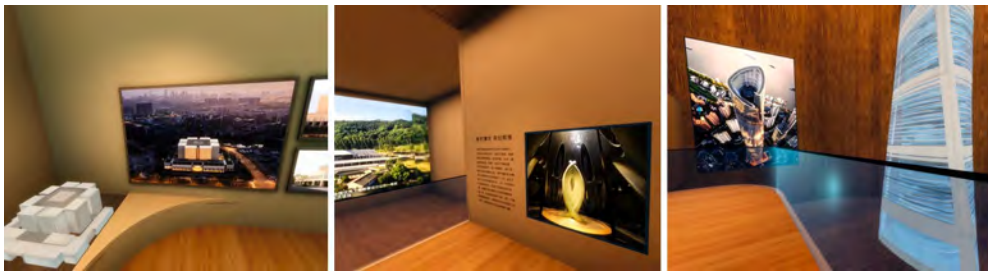

Fig. 9: Recorded VR scenes

3.2 Interview Results

On reviewing the interview answers and being on site, we saw several obvious trends in the manner in which people experienced the mobile VR immersive gallery. Regardless of the situation they were in, participants frequently reported the VR environment as very engaging and easy to navigate through. Some people said it made it much easier to grasp design concepts and conversations about design suggestions. Figure 10 reveals the key themes summarized from the interview responses.

In the studio reviewing atmosphere, people frequently discussed how VR was the vehicle for them to have a way of understanding space. Faculty and outside critics said that working with things in 3D made it a lot easier to get a sense of things like scale, spatial relationships and the main ideas behind a design, especially if the sites were complicated. A number of reviewers would tell us they were able to very easily piece together what a project was about if they were in the virtual world. These reviews, students say, had also made them feel more engaged. The discussions turned more focused, because the reviewers could literally point to what was out in the VR world instead of their looking at drawings. Some students also realized this way lifted the pressure from their presentations and made design-in-the-mind the most important thing to get a response on.

Throughout the design presentations for the exhibition space, people made this point so much, that the VR gallery was the most immersive and exciting. A number of said that they were more excited about the space now after experiencing it in VR. The virtual setting provided a stage for designers and artists to flaunt spatial concepts that would have been difficult or even impossible to make in the real world. Unusual layouts, sizes, and moods could be explored without limits. People also thought that being immersed in the VR space helped them connect with the artworks more deeply. Some of the space design and art pieces appeared clearer and more powerful as a result of their virtual settings. A number of interviewees also noted much of the visual cohesion among space and art, audience and observer was much more easily spot on in VR.

At the industry expo, people said that the VR immersive gallery was something that caught their attention and remained with them. Many said they took more time exploring the firm’s work than they would normally at such an event. The immersive feeling left them curious and eager to look around. Interviewees also linked their VR setup with high-tech and futuristic design. This gave them a positive impression of the company and increased their interest in the company's work.

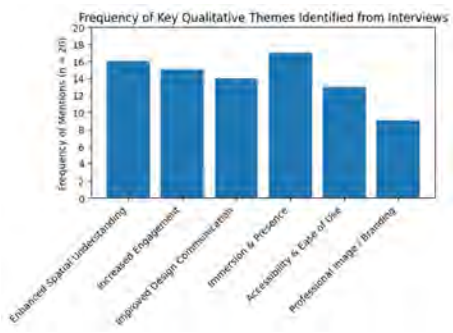

Fig. 10: Themes from interview

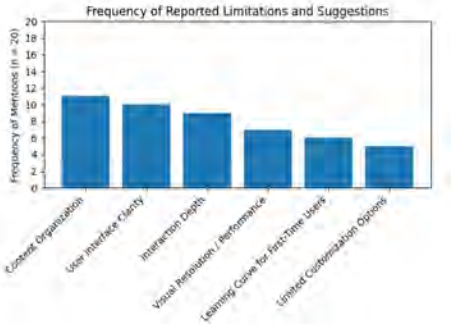

Fig. 11: Limitations from interview

In every context, people repeatedly returned to three enormous strengths of the VR system: immersion, interactivity and ease of access. Meanwhile, they also gave some good ideas as to how to do things better, such as clearing up the organization of content, refining the UI, and incorporating greater interactivity (Figure 11). Several people also mentioned how useful it was that the setup was mobile and wireless because it made it much easier to use the VR gallery in different places without a lot of hassle.

3.3 Discussion

The findings of this study demonstrate the broader potential of the mobile VR immersive gallery as a versatile visualization tool for design-related activities. Across all three scenarios, participants reported enhanced spatial understanding, heightened engagement, and improved design communication. The interactive and immersive nature of this virtual environment enabled users to perceive spatial relationships, scale, and design intent more intuitively. As a result, design concepts are easier to articulate and discuss, strengthening communication among designers and multidisciplinary participants. The variation in user feedback across scenarios can largely be attributed to contextual differences. Within the educational setting, the VR gallery primarily facilitated spatial comprehension, focused critique, and collaborative discussion. In professional and public-facing contexts, it served as a tool for communication, representation, and audience engagement. Despite these contextual distinctions, participants across all settings expressed consistently positive evaluations. This suggests that the core attributes of this mobile VR immersive gallery, mobility, flexibility, and immersion, are transferable across diverse design applications. Unlike traditional wired VR systems that rely on fixed computer connections and specific technical infrastructure, the mobile and wireless feature of this VR solution allows rapid deployment in any space without extensive setup or site-specific adaptation.

Beyond logistical convenience, the system leverages a perceptual advantage in immersive virtual environments. Within a relatively small physical area, users experience expansive and complex virtual spaces through carefully constructed spatial sequences and navigational paths. Because perception of distance and scale is highly influenced by immersive cues in VR, participants can experience the sensation of moving through large space while physically remaining within a small space. This spatial compression enables substantial amounts of design information to be represented within limited physical space, enhancing efficiency while maintaining cool experience. The findings further indicate that mobile VR platforms can

overcome practical constraints related to space, configuration demands, and operational complexity. By reducing technical barriers while preserving immersive performance, the mobile VR gallery expands access to immersive visualization in both academic and professional settings. Rather than serving simply as an innovative visualization tool, it operates as a flexible spatial interface that transform how design content is experienced, communicated, and understood. In addition to improving spatial understanding and communication, several participants described the experience as relaxing and emotionally restorative. This suggests that the mobile VR immersive gallery may extend beyond visualization in design-related activities and hold potential for applications in therapeutic, meditative, or other experiential contexts. Further research is needed to examine these affective effects more systematically.

3.4 Limitations and Future Research

This study has several limitations. First, the sample size is relatively small. This is because that the VR immersive gallery was deployed within real-world design activities rather than controlled experimental settings. Participants are recruited onsite during each activity so it is difficult to conduct long and comprehensive interview or survey. Meanwhile, the limited number of VR headsets and the specific area of spaces also constrained the number of users and their availability for complicated user studies. As a result, this research prioritizes implementation feasibility over rigid experimental control. Larger sample (at least 50 participants) should be involved in future studies. Second, data collection relied primarily on semi-structured qualitative interviews. While this approach captured rich experiential feedback, the findings are exploratory and not statistically generalizable. In future work, more structured evaluation approaches such as survey, quantitative perception studies, and behavioral measures should be incorporated. Third, only three application scenarios were examined. Although these represent educational, professional, and industry contexts, future research could extend its scope to additional settings such as community engagement workshops, participatory planning sessions, high school recruitment events, and interdisciplinary design charrettes. In summary, larger sample size, mixed-method approaches, and longitudinal assessments will be necessary to better evaluate the effectiveness and broader impact of the mobile VR immersive galleries developed in this research.

4 Conclusion

In this research, a mobile VR immersive gallery with a variety of design settings (including design education, professional exhibitions, and industry presentations) is studied. Through creating a flexible, wireless VR system while examining qualitative narratives of user experiences, we illustrate how immersive visualization supports spatial perspective, interaction and design communication by the way that user interaction enhances their experience of environment. The results show that a single mobile VR gallery can be tailored to various application scenarios without major technical modification or the need for site-specific infrastructure. In all three scenarios, user responses demonstrate that the immersive and interactive nature of the VR environment can support a clearer understanding of spatial qualities and enable better communication between designers, reviewers, users, and stakeholders. These findings support the use of mobile VR immersive galleries as a pragmatic and flexible visualization technique for a range of design activities, however limited in sample size and qualitative scope.

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A Speculation on Interacting with Information in Public Space: Using Augmented Reality to Create an Alternative Media Infrastructure

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Abstract: Public spaces, beyond direct communication between individuals, also support communication with the public through urban media, which has the potential to support the public's access to critical information and raise awareness on various issues. Therefore, this study speculates on an alternative urban media infrastructure that spreads throughout the city through public spaces and supports the public in obtaining information regularly. Accordingly, it first examines the current urban media practices through a field study and further questions them while speculating on the use of augmented reality as an alternative media infrastructure for information dissemination.

Keywords: Urban media, public space, augmented reality, data visualization, speculative design

1 Introduction

In today's rapidly changing and developing world, it is important for individuals to acquire information on various issues and be knowledgeable about them. On one hand, information acquisition can occur through individual efforts in private spaces such as homes, in semi-public spaces such as libraries, or as part of a shared experience in semi-public educational spaces such as universities and exhibitions. On the other hand, public spaces such as streets, which not only provide a place for direct communication between people but also support communication through carrying messages (BARBAUX 2010), also have significant potential for information acquisition by being part of people's daily flow.

Historically, the first urban messages were road signs, which were introduced in Roman times and formalised for the first time in France in the 19th century. They continued to develop, with the first red and green traffic lights appearing in England at the end of the century, followed by traffic signs such as the stop sign in Detroit in 1914 (BARBAUX 2010). However, the messages had gone through changes. One of which happened with the emergence of outdoor advertising. The transition to an industrial economy in the 19th and 20th centuries, with advances in manufacturing and production, required new areas for displaying these products, and the centers of social life were chosen for this (SILLA 2020). Accordingly, advertising, which began to be a part of cities with shop signs in the Middle Ages, took the form of posters in the 19th century, and over time, new forms of urban furniture, such as the Mupi, began to emerge (BARBAUX 2010). While this kind of urban media has been primarily aimed at displaying advertising content, it has been used to communicate topics of public concern, too such as posters to give information about laws in 19th century (BARBAUX 2010) or use of out-of-home advertising surfaces, such as billboards or transit advertising surfaces, for communicating preventive behaviours on Covid-19 (MOHAMADPOUR et al. 2024) or climate change (WILSON et al. 2021) in more recent times.

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While these practices have demonstrated the use of communication-focused urban furniture for displaying critical information, they have largely remained singular instances in the everyday use of the urban media infrastructure, and a more continuous approach to display such information remains lacking. Thus, this research questions what an urban media system that spreads throughout the city through public spaces and supports the public to obtain information regularly could be like through a speculative design approach. To achieve this, a two-part study was conducted. The first part examined the current state of media infrastructure in urban public spaces through a field study conducted within a defined sample area during non-targeted dates and times to reveal the everyday use of urban displays that are part of urban media on any given day. In the second part, speculations were developed for an alternative urban media infrastructure that utilizes augmented reality (AR) technology. In this context, a discussion was conducted on AR drawing from the findings of the field study; various scenarios were then developed on possible uses of the system in public spaces, and a low-fidelity prototype was developed to explore and reflect on technical and experiential potential.

2 Examination of The Current Urban Media Practices

The first part of the research focuses on understanding the current state of everyday use of media infrastructure, specifically urban displays, focusing on two of the media infrastructure dimensions, material and content (SCHILLER 2020). Accordingly, a field study was conducted in Kadıköy, one of the centers of the city of Istanbul, on a route approximately 450 meters long that was determined based on pedestrian movement on the site. To ensure diverse media practice, the determined route encompassed various landscape typologies, including vehicular traffic, pedestrianized spaces, and transportation hubs for different modes of transportation. The field study was conducted in two stages. The first stage aimed to provide an overview of the urban display practices in terms of their material aspect and the relationship of the material aspect with urban public spaces. The second stage focused on the content dimension of what we called managed displays, a subset of urban displays defined based on the examination conducted in the first stage to reveal what was communicated to the public.

2.1 Examination of Materials of Urban Media

One of the dimensions of the media infrastructure is the material dimension (SCHILLER 2020). In the context of this research, this referred not only to the displays but also to the physical elements in the urban environment that carry some form of media or display. They were categorized and further discussed under two topics: their dedication status and the display technology they use.

Status of dedication: Field study revealed that only a portion of the content-carrying elements in urban open spaces are elements specifically incorporated into the city for this purpose, such as communication-focused urban furniture, while the rest are non-dedicated carriers that have transformed into media surfaces. Their transformation is found to happen either by direct application without any structural changes on the carrier, such as affixing print-based media or through direct inscription (e. g., graffiti), or by being appropriated through material fixtures, such as attaching digital screens. While dedicated carriers inherently managed media outlets with authorized content, the management status and the content's authorization status of non-dedicated carriers vary. For instance, while a screen attached to the façade of the ferry

terminal, a non-dedicated carrier, was found to be managed based on its content and display behaviour, a temporary barrier was identified as not managed, based on the flyposting activity which is quintessentially unauthorized and independent (BLACK & NEVILL 2009), that occurred on it.

Display technology: The study area was found to contain various display technologies, both non-digital and digital. The identified non-digital displays in the study area included print-based approaches (e. g., posters, signs); direct graphical text (e. g., graffiti); and physical objects (e. g., 3D signage). Digital displays consisted of screens varying in size, spatial arrangement, number, and configuration: for example, attached single-sided screens at eye level, stand-alone double-sided elevated screens. Two key elements determined by the display technology were identified: the medium and the presence of content. Accordingly, in cases where non-digital approaches were used, the content was limited to static images, while both static and moving images were displayed on digital screens. The second element determined by the display technology was the temporality of the content's presence. Accordingly, some content was continuously visible, while other content was visible for a specific period; this imposed a temporal condition on interaction with the content. Two scenarios were possible for non-digital displays. In the first, a single piece of content was continuously accessible without time constraints, allowing the interacting party to determine the duration of the interaction. In the second, content items were rotated in a defined order using a scrolling mechanism that limited the number of items a carrier could possess and transmit to three. Unlike non-digital displays, digital displays have the ability to make a piece of content visible/accessible for a certain period of time and to display multiple pieces of content consecutively. This can lead to the accessible content differing for those passing by the same point at different times, and also results in an interaction where the duration is not determined solely by the user.

2.2 Examination of Contents of Urban Media

The review phase of the content dimension of urban media infrastructure aimed to examine the types of content the public encounters in public spaces, particularly the presence of educational and informational content. The examination was limited to the content of managed displays. The content collection was done on the same day for all displays. Accordingly, 19 urban media elements were identified along the defined route. 4 of these were single-sided, and the 15 included two or more sides that display content. 11 of these 15 were carrying content independent from each other on each side, and 2 of the remaining were double-sided and were simultaneously carrying the same content on each side; 1 had two perpendicular sides that carried single content that spanned both sides; and 1 had 4 perpendicular sides that either displayed single content or spanned content. As the content displayed by different surfaces of these carriers was the same or connected, they were handled as a single unit. Data collection was done by recording the content of the defined displays. While the content of the static poster carriers was directly visible, for the scroll poster mechanism, their rotation was followed to record all the posters. One scroll poster mechanism was handled as a static poster, with the visible poster as it malfunctioned. To identify the content displayed on digital screens, data was collected for 10 minutes on each digital screen. Content whose start and end frames did not fall within this time frame was excluded from the dataset. Content collected from digital displays, the continuously accessible pieces of content on posters, and rotating content on scroll posters were analyzed, and 98 different pieces of content were found to be displayed via managed displays along the defined route. These contents were

categorized based on the type of information they were communicating. While the majority of the content was advertisements of products, brands, and cultural events such as theatre plays, three pieces of content were identified and categorized under public awareness as they were informing the public about criticalissues that are of public concern. Two of these contents were published by the Istanbul Metropolitan Municipality and focused on preventing water waste. One of them carried the text (translated from Turkish) “Now is the time to use every drop carefully. Let's use our water sparingly, let's not waste it for our future.” And the other carried the text (translated from Turkish) “Every drop holds the future. Every drop you protect today will give life to tomorrow.” The last public awareness content was about the electronic waste campaign of a private company. While these contents were aiming to raise public awareness, they only contained a direct message for behaviour change, yet did not include information on the topic. One crucial issue is that because these contents were displayed on a digital screen that displays contents on rotation, the public awareness contents were not visible at all times, which was a limiting factor on the number of people who saw these contents. Two additional contents were also identified that were not part of the initial corpus due to their carriers, one permanent panel giving information about tsunami escape routes placed on the coast, and a content about blood donation displayed on the façade of a related building.

The analysis also revealed some level of relation between the content and the location. While some content, such as product advertisements, had no relation to the location, the content published by the local government regarding their activities in the city where the content was displayed defines a relation with the location. Furthermore, the tsunami escape map placed in the related location also defines a relation between content and location. Furthermore, it was observed that a digital screen located near a theater stage currently under renovation was heavily displaying content related to theater productions. While it cannot be definitively stated whether this was intentional, it still defines a relation between the location and the content.

3 Speculation on an Alternative Media Infrastructure

Speculative design “…aims to open up new perspectives on what are sometimes called wicked problems, to create spaces for discussion and debate about alternative ways of being...” (DUNNE & RABY 2013, 2). This speculative design study identifies the lack of display of critical information in urban media as the wicked problem and envisions an alternative urban media infrastructure that spreads throughout the city, is dedicated to displaying critical information, and supports regular engagements with new information. It follows, imagining alternative presents based on current technologies (AUGER 2013) approach of speculative design, but instead of focusing on using existing public display technologies that were identified on field study in new ways to imagine an alternative present, it employs AR technology, which is currently available but whose use in this context has not been sufficiently explored. During this process, it refers to findings of the field study, challenges the available technologies, and is challenged by them.

3.1 Discussions on the Use of AR

SCHILLER (2020) defined three dimensions of media infrastructure, which are materiality, content, and poetics. In the context of this research, which focuses on public space, this refers

to media practices that display public content on public displays in public space to be engaged with publicly. While the current media practices were in line with this premise, AR challenges the publicness aspect of an urban media infrastructure, in particular, its material aspect. With their widespread use in streetscape, private displays such as mobile devices, which are now a type of urban screen (MCQUIRE 2009), have enabled the display of private content in public spaces. On the other hand, by supporting AR, these private displays also allowed people to view public content in public spaces, suggesting that the publicness of the displays can be challenged. However, although the content remains publicly available and the experience remains public, it is only publicly available and publicly engageable if the members of the public have ownership of a technologically capable device and the know-how to use it to engage with the content. Otherwise, this may lead to a digital divide, which refers to the gap caused between people as a result of access to new information technologies (VAN DIJK 2006).

AR also challenges the material dimension of public display practices, in terms of presence in space and physical integration to space. In current public display practices, the display is positioned within the physical environment and is constantly present. In contrast, AR changes this situation by enabling a transition from public displays to private displays, transforming it into a non-permanent inclusion in the public space while in use. Thus, while it is not a physical component of space, it is present in space. On the other hand, the type of tracking technology AR uses may also impact its presence in space and its physical integration into space. For example, while marker-based AR needs a physical marker, such as an image, to determine the placement of the digital objects, location-based AR utilizes position data, such as GPS coordinates collected from the mobile device, to display content (CHENG & TSAI 2013) without requiring any physical component integrated into a physical environment.

The physical presence in space and physical integration can be discussed from two different perspectives: as an indicating factor or as a limiting factor. Even though this physical presence does not guarantee engagement, as proven by phenomena such as the display blindness, which refers to ignoring public displays in the assumption that they carry uninteresting content (MÜLLER et al. 2009), a digital screen or a poster still indicates that some kind of information is present. So, in the case of the use of marker-based AR, the marker not only activates AR but also indicates the system. In the case of location-based AR, however, the indication may be sustained by the digital one, such as a notification stating the availability of a data point in imidiate environment. Yet the difference between these two indicators is that while the physical one also allows people who are not familiar with the system to become aware of it, the digital one is only available for those who already know about the system and use it.

The second perspective on physicality is that it is a limiting factor. In the current urban media infrastructure, the content can only be made available if the material means are in place, e. g., the content can only be displayed if a digital screen is available, or a poster can only be placed if the carrier is available. Thus, the materiality dictates where the content can be displayed. On the other hand, AR, which requires little or no physical equipment based on the type of tracking it utilizes, enables easy integration into new locations. Thus, the location of the display adapts to the needs of the content and engagement.

3.2 Possible Integration Scenarios and Prototyping

In the final stage of speculating on the use of AR to create an alternative urban media infrastructure. Accordingly, the material dimension of the infrastructure is personal devices that would display the augmented content and markers when it is the chosen tracking system. The content dimension would focus on data and information visualizations that would extend the current practice of direct messages for behaviour change without information, as identified during the field study. Lastly, while the poetics dimension, which refers to what the infrastructure signifies or means to its users (SCHILLER 2020), cannot be addressed as a scenario, the environment in which the experience would take place and the manner in which it is experienced can be. Overall, we envisioned scenarios for integrating the system into the city based on the physical properties of the space, the function of the space, and the narrative value of the space (Figure 1).

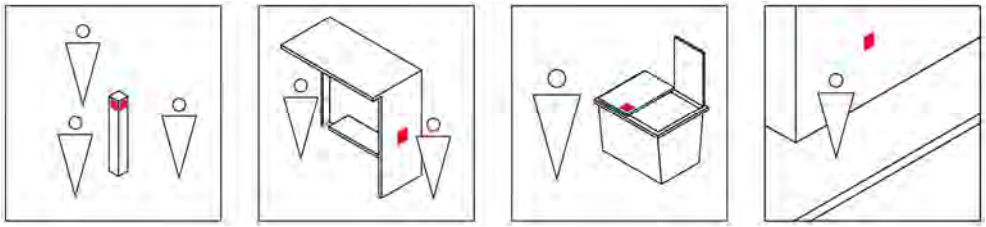

Fig. 1: Envisioned scenarios for the integration of the system into the city

Physical properties of space are a defining factor in how a display can be placed in a location as well as how it is interacted with. FISCHER & HORNECKER (2012) found that an interactive display defines different types of space around itself, one of which is interaction space, and they found that when the interaction space is small, people do not occupy the space together but wait and observe, rather than interacting, and social interaction would not occur. On the other hand, the honey-pot effect suggests that a person interacting with the display can make others get interested too (BRIGNULL & ROGERS 2003, MÜLLER et al. 2012), which a large open space can facilitate. This may also facilitate social interaction and conversation between people, which is one of the design recommendations of PARKER et al. (2020) to achieve interactive display deployments that provide value for their users. Accordingly, one integration scenario would take place in a large open space, such as a park, in a way that allows multiple people to interact with data simultaneously: *"You are sitting on a bench in the park, you saw a couple of people gathered over there pointing their phones at the same point, you go over there, open the app, and view the content. One of the people says to you -How interesting is this!"* On the other hand, it is also possible to integrate the system in small spaces such as on a street that allows short-term stops if it is necessary to display the content in a particular location even if the physical properties of space do not allow such interaction, or it is not wanted: "*You are passing through a street and see a data point sticker on a building façade, which you realized was not there last week. You think it must be new; open the app and view the content.*"

Function of the space impacts the actions of people; thus, where interaction is positioned impacts the chance of opportunistic interactions (PARKER et al. 2020). For example, people tend to engage with the displays at times when they wait without anything else to do (MÜLLER et al. 2009): "*You left home for work and arrived at the bus stop, and you noticed a sticker*

bearing a data point emblem. Your bus leaves in 10 minutes. You could try out the new data point while you wait."

Physical environment can be part of the narrative and can add value to the narrative. In the field of data visualization, this relates to situated visualization, which means "visualization displayed in the relevant spatial and semantic context" (WHITE 2009, 15). *As you threw your trash into the bin, you noticed a data point sticker on the bin. Isn't this an interesting location for a data point, or perhaps some content related to waste?"* On the other hand, it is also possible to establish a local narrative, thus positioning physical environment as a place rather than space (BRESSA 2022) which has proven to enrich the knowledge of the public regarding social issues, facilitates social interaction (CLAES & VANDE MOERE 2013), and encourages public discourse on local matters (KOEMAN et al. 2015). Accordingly, such a scenario continues *"…but wait, isn't this about your building?"*

Subsequently, a low-fidelity prototype was created where a marker was used as the tracking technology for AR (Figure 2) for a scenario where space adds value to the narrative.

Fig. 2: AR view of the data visualization about waste segregation behaviour

The subject of the data visualization was determined as the waste sorting behaviour of people in the Kadıköy district of Istanbul, and it was imagined to be displayed on a trash can located on a street within this district. This relationship between data and physical context also would define the visualization to be a situated one (WHITE 2009). The relevant data was collected from the "DDMM Segregation of Domestic Waste in Houses by District" dataset that was published by the ISTANBUL METROPOLITAN MUNICIPALITY (2023). Data visualization was created using Blender modelling software, and AR was developed in Unity, utilizing the Vuforia SDK. The prototype was created as a proof-of-concept and exploratory study to identify potential design issues with such a system.

4 Discussion and Outlook

This two-part research is a speculative study on urban media. It first presents a brief analysis of contemporary urban media practices through field study in a sample area, and then uses

these findings to speculate on an alternative approach utilizing AR technology. One of the key points is the limited amount of content available in current urban media practices, particularly within managed public media infrastructure, and the fact that this content often lacks factual information but consists of messages aimed at influencing public behaviour. While data visualization, the proposed type of content, offers an alternative approach, it may raise issues to consider, such as the data literacy of the public. Another key issue is the physical presence of existing media outlets, which also act as the indicator of where to expect content, but the predetermined nature of these outlets acts as a limiting factor in the narrative-space relationship. This was explored through the proposed system, highlighting the potential for adapting AR to the city due to its minimal or no physical equipment needs. Overall, this study, rather than presenting a definitive design, aimed to emphasize the role of public space as a space for awareness, learning, and discussion by examining the current urban media speculating on an alternative media infrastructure.

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Digital Tools, Data Systems and Software

Spatial Analysis of Proposed Planting Design Using *DepthmapX* Software: A Case of Shenoy Nagar Metro Station Urban Park, Chennai, India

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Abstract: The landscape design process progresses from conceptual frameworks to detailed, spatially organised outcomes. Design decisions are informed by both professional experience and systematic analysis. Space syntax serves as an analytical method for interpreting spatial language through configuration, visibility, and accessibility, thereby connecting the physical, psychological, and social aspects of space. Prior studies have applied space syntax to assess green space design quality, analyse pathway configurations and senior walking behaviour, and evaluate accessibility and pedestrian movement to predict trail usage. However, few studies have systematically examined how tree form and placement within urban park environments can be strategically manipulated to enhance visual experience, especially in the context of fluid boundaries common to green spaces shaped by gateways, walls, buildings, and tree canopies. This study advances prior work by integrating space syntax with detailed planting plans to quantitatively assess the visual and spatial impacts of tree arrangement in Thiru-Vi-Ka Park at Shenoy Nagar Metro Station in Chennai. By conducting intelligibility analysis across four clusters, we provide new insights into how specific spatial configurations and species selection shape visual fields *($p < 0.001$),* generating high- and medium-level visual-field experiences through the arrangement of fifteen native and naturalised tree species. This approach not only extends space syntax methodology to more nuanced aspects of urban green space design but also establishes a framework for evidence-based planting strategies that respond to the complex, dynamic boundaries of contemporary parks.

Keywords: Space syntax, *isovist*, intelligibility analysis, connectivity, visual integration

1 Introduction

Space syntax investigates human interactions with spatial environments, emphasising the layouts of buildings, roads, cities, and landscapes. This analytical method enables architects, urban designers, and planners to assess how spatial arrangements influence social, economic, and environmental outcomes. Using quantitative data, space syntax demonstrates that the significance of a space derives from its configuration, which in turn shapes patterns of human interaction. The theoretical foundation posits that space is experienced through movement. Physical movement is analysed through concepts such as convex spaces, defined as areas where you can draw a straight line between any two points without crossing outside the space. *isovists* show what can be seen from a certain spot (VAN NES & YAMU 2021). Spatial configuration considers not only individual spaces but also the connectivity between different areas within a building or urban context (KARIMI 2023). In the present study, tree planting was selected as the focus because trees are highly visible along visitor pathways and are distributed throughout the park, offering a diverse range of groupings and distances. The research investigates how planting design in urban parks is achieved through the application of space syntax. The design methodology emphasises straightforward planting schemes at the pedes-

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trian scale, utilising *DepthmapX* to analyse the legibility of spatial groupings formed by the fifteen selected trees, to enhance visitor navigation.

2 Space Syntax: Theory and Agent-Based Model in Planting Design

Space syntax looks at how people, and the spaces they use, such as buildings, roads, cities, and parks, are connected. This approach uses graphs to examine how the layout of spaces affects social, economic, and environmental outcomes, and provides measurable ways to describe built environments. The way spaces are arranged shapes social meaning and how people interact. The theory holds that space can be studied objectively and that people naturally engage with it. People experience space by moving through it, using open areas and visible zones called *isovists*. This study uses space syntax to examine how the arrangement of trees shapes people's experience of planting design in city parks. Research in environmental design combines methods for studying what people can see with computer simulations and virtual reality. For example, some researchers used virtual agents in computer environments to create *isovists* that show what can be seen from different spots. Others built systems to make *isovists* or studied how people see and move along paths using virtual reality (NOYMAN et al. 2024). Some researchers say that visibility studies should include height and depth, not just flat layouts. Although they sought to study three-dimensional openness, they were constrained to two dimensions by the limitations of the computer. Another researcher looked at the amount of sky visible from different places in cities, calling it sky-opening, which gives a way to measure openness that does not depend on size. Others mapped how much sky people see from different spots to measure how open a space feels (XIA et al. 2021). Some argue that while these methods add a three-dimensional view, they mostly measure what people notice by sorting and judging what is seen (VAN NES 2008). This research builds on these ideas by examining how different planting strategies create distinct spaces in landscape design. Space syntax suggests that the way spaces are arranged is closely linked to social structure and that spaces have their own social logic. In landscape design, this means outdoor areas are planned to encourage interaction by dividing them into clear, easy-to-understand sections. These sections support different groups, activities, and behaviours, showing cultural values and social structure. Space syntax does not view space merely as a container for society. The main ideas are integration and connectivity. Integration is the number of steps or turns it takes to get from one place to another, measuring how easy it is to move through the space rather than just the physical distance. Each path has its own level of depth and integration in the system. A space is more integrated if it is easier to reach from other places, and more separated if it is harder to reach. Connectivity is the number of direct links a place has to other places. Important measures include connectivity, path length, and clustering. How spaces are integrated is linked to how people move and behave. Some studies found connections between how people understand space and its integration, and other studies support these findings (YUNITSYNA & SHTEPANI 2023). These results show that space syntax helps analyse how planting affects people's movement. Many methods have been created to study real city environments. Space syntax treats city space as a network of connected areas and analyses how they are arranged using computer-generated graphs. These graphs show patterns in city layouts and how people use them. What people can see and how they see it are important for how they enjoy (LI et al. 2023) outdoor spaces, which matters for landscape

design. Studies have found strong connections between how spaces are arranged and how people use them. For example, one case study in London measured the amount of greenery people could see at street level using space syntax and crowdsourced images (CHEN et al. 2025). The method people walk or drive can be predicted using a local integration measure from the visibility graph. *Isovists*, or viewshed polygons, show what can be seen from a given spot, using details such as location, edge length, number of corners, and boundary features. But *isovist* analysis misses bigger spatial relationships. To fix this (ASKARIZAD & GARAU 2026), researchers developed Visibility Graph Analysis (VGA), which examines how visible different parts of an area are to one another and provides measures such as integration and spatial clustering. VGA has been shown to predict better how people move in open outdoor spaces than older methods. Agent-based models are important in space syntax for simulating how people move. Some researchers modelled how visitors move as agents following simple movement rules based on what they can see and moving step by step. They found that where people arrive and how long they stay are closely linked to how people move (SUTKAITYTĖ 2021). This model examines how people get around and helps determine whether a design meets social needs. This study uses this method to examine how different planting design layouts affect how people use space.

3 Study Area, Planting Design Proposal and Analysis

3.1 Study Area-Synopsis

The study area is Thiru-Vi-Ka Urban Park, located in Shenoy Nagar, a residential area of Chennai, Tamil Nadu, as shown in Figure 1. The site is on the eastern coastal plains at 13°04'12"N, 80°23'32"E, with an average height of 11.50 meters above sea level. The climate is Tropical Savanna, which means it has wet winters and dry summers. The original park covered 8.8 acres with about 328 trees. In 2007, the park was improved for 6.4 million INR. It was closed in 2011 for Chennai Metro Rail construction, during which most trees were removed. After the metro work finished in June 2015, the park was rebuilt for 40 million INR and opened again on 4 April 2023, as shown in Figure 2.

Fig. 1: Location Map of Case Area: *Thiru Vi Ka* Urban Park (Source: Photomontage by the Author from GOOGLE Map, October 2025)

Fig. 2:
Study area and location of trees
(Source: GOOGLE Maps, October 2025)

3.2 Spatial Analysis and Measurement Technique

The spatial analysis method uses shapes that show what can be seen from each spot, generated from a grid covering all walkable city areas. Researchers used two main measures, global visual integration and local visual clustering, to study Thiru-Vi-Ka Urban Park in Shenoy Nagar, Chennai. Visual integration shows how each place connects to the whole area. Visual clustering is important because it matches how many people walk through certain points. It measures how far the view from a given spot extends in different directions, with scores ranging from 0 to 1. This measure shows how likely people are to encounter one another and interact. The study used a tool called *DepthmapX* to look at visibility. A statistical model was used to analyse planting patterns from different groups of 15 trees each. Curved layouts were tested to look at Bell's idea about visual balance in landscape spaces.

3.3 Proposed Planting Design

Fig. 3:
Proposed clusters and planting design
of the case area: Thiru-Vi-Ka Urban Park
(Source: Author)

3.3.1 North West Cluster

The tree planting plan considers species, mature shape and size after 20 years, growth rate, summer leaf cover, and branch openness. In the northwest, evergreen trees – *Putranjiva roxburghii*, *Syzygium cumini*, and *Thespesia populnea* – are arranged in a circle and spaced along a line to create a defined edge. These species grow at fast or medium rates, have broad forms, and provide leaf cover values of 3.25, 1.80, and 1.16. In the centre, trees are grouped and spaced in a winding pattern to create visual interest. Selected species include both deciduous *(Ficus religiosa, Albizia lebbeck)* and evergreen *(Mimusops elengi)* trees. All are broad and rounded, with varying growth rates and leaf cover values ranging from 1.30 to 2.21.

3.3.2 North East Cluster

A rigid geometric form characterises the architectural program for this cluster. To complement this, trees are arranged to create an enclosed circular space that supports the planned facilities. Evergreen species, including *Tamarindus indica* and *Azadirachta indica*, are proposed in a single, regular circular pattern with detached spacing. These species exhibit a leaf area index (LAI) of 3.27-3.11 and are slow-growing. At the centre of the cluster, *Terminalia catappa*, a fast-growing, pyramidal deciduous species with an LAI of 3.33, is proposed as an accent tree, arranged in a regular pattern with meandering spacing.

3.3.3 South East Cluster

For the South East cluster, facility space planning specifies edge planting to create an enclosure using a single evergreen species, *Syzygium cumini*, which has moderate growth and a leaf area index (LAI) of 1.8. These trees will be arranged in a regular pattern with detached spacing. End markers along the enclosure will use the evergreen *Manilkara hexandra*, a slow-growing species with an LAI of 2.11.

3.3.4 South West Cluster

The South West cluster should include an enclosed circular space with a meandering edge, planted with a single evergreen species such as *Azadirachta indica*. Select a fast-growing species with a leaf area index (LAI) of 3.11, arranged in a linear, regular pattern with consistent spacing. *Cassia fistula*, a broad, fast-growing deciduous tree with an LAI of 1.15, is in the central enclosure. Arrange these trees in a regular circular pattern with detached spacing.

3.4 Visibility Graph Analysis

A visibility graph was generated in *DepthmapX* to assess spatial organisation, incorporating all five gates and the two entrance points of the southeast and southwest clusters. A 0.60-meter grid ensured coverage of all visible and accessible areas. At each grid point, the visible area was mapped to establish direct links between points (Fig. 4). The resulting graph was analysed to understand spatial arrangement and perception. Yue and colleagues demonstrated that deep learning can analyse street view images to identify key pedestrian and circulation areas by evaluating multiple visual qualities (YUE et al. 2025). The relationship between connectivity and integration reflects the intelligibility of spatial configuration (KUYRUKÇU &

Fig. 4:
ISOVIST Analysis
(Source: Screen view adopted by the Author from *DepthmapX*)

ÇINAR 2023). Studies from the past have exhibited that visual integration is linked to pedestrian movement (DESYLLAS & DUXBURY 2001).

3.5 Gate Count Analysis

Table 1: Gate Count Analysis of all clusters *vs* Connectivity-Regression value *(p <0.001)*

Cluster	Minimum	Average	Maximum	R^2
NW	1	58.10	296	0.51
NE	2	60.94	263	0.42
SE	1	68.12	351	0.32
SW	1	58.94	303	0.34

Calculations were performed within the proposed urban park environment. To estimate movement patterns, a theoretical gate count of 100 per gate was assigned in the designed area. The *DepthmapX* agent tool was used to predict anticipated gate counts by simulating pedestrian movement grounded on the spatial configuration of trees (TURNER 2003) establish that this tool is predictive of theoretical movement (HILLIER & IIDA 2005). Table 1 presents the numerical gate counts for each cluster, as exported from *DepthmapX*, along with the regression values for each cluster in the case area. Gate-count data from each cluster proposal were aggregated into a single image to illustrate spatial configuration and pedestrian movement, as analysed through space syntax measures (Fig. 5).

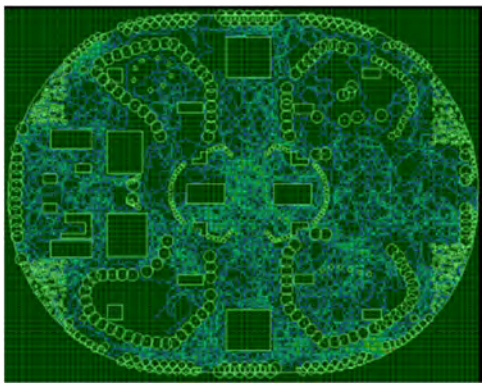

Fig. 5:
Gate Count Analysis
(Source: Screen view adopted by the Author from *DepthmapX*)

3.6 Intelligibility Analysis

The planting design, spatial appearance, and pedestrian movement were analysed using Visibility Graph Analysis (VGA). Figure 6 illustrates the visual assessment of the planting designs. Clusters with wider openings exhibit higher levels of global integration. Connectivity values range from 2 to 2119 in the northwest (NW) cluster (average 1001.10), from 2 to 2146 in the northeast (NE) cluster (average 1003.10), from 2 to 1543 in the southeast (SE) cluster (average 670.09), and from 4 to 1193 in the southwest (SW) cluster (average 695.40). Visual integration values range from 2.10 to 9.92 in the NW cluster, 1.89 to 8.95 in the NE cluster, 2.11 to 7.21 in the SE cluster, and 2.29 to 7.85 in the SW cluster. Connectivity demonstrates a strong correlation with visual integration (HH). The NE cluster exhibits the highest coeffi-

cient of determination ($R^2 = 0.76$), followed by the NW ($R^2 = 0.63$), SE ($R^2 = 0.56$), and SW ($R^2 = 0.43$) clusters. The East-West central plaza records the highest R^2 value (0.86), followed by the North central plaza (0.86), and the South entrance plaza with the metro station (0.46).

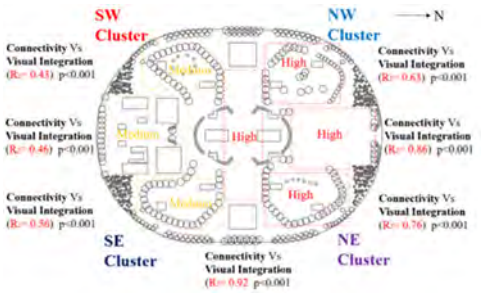

Fig. 6:
A summary of Connectivity *Vs* Visual Integration *(HH): Thiru-Vi- Ka* Urban Park (Source: Author)

4 Proposed Planting Design Spatial Configuration on the Visual and Social Structure: A Discussion

Trees do more than fill outdoor spaces; they shape how we experience them. This study explores how various planting styles transform what visitors see and how they navigate Thiru-Vi-Ka Urban Park, using the *DepthmapX* tool. Researcher mapped out four key zones – northwest, northeast, southeast, and southwest – plus the plazas that link them. The results reveal that tree placement powerfully shapes both sightlines and the flow of space *($p < 0.001$).* This approach proves valuable for designing tree layouts that benefit both planners and park-goers. The research highlights two main types of visual journeys, High and Medium, each tied to distinct planting patterns. Sweeping tree-lined curves and generous entrances open up broader views of the park. At the heart of the park, curved spaces create a stronger bond between the stability of the view and the arrangement of trees. Introducing 15 tree species, both native and well-suited newcomers, in flowing curves and straight lines across the plazas changed how people moved and connected. Embracing a more organic, free-flowing planting style enriched the visitor experience. In the end, the Agent Trail (Fig. 7) shows that intentional tree planting not only guides people and sparks social encounters but also makes the park more inviting and vibrant.

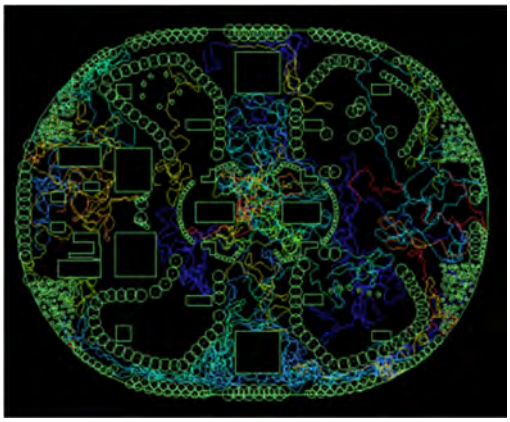

Fig. 7:
A summary of *"Agent Trial"* Analysis, Case Area: *Thiru-Vi-Ka* Park (Source: Screen View adopted by Author from *DepthmapX*)

5 Conclusion and the Way Forward

The proposed tree planting pattern was developed using UCL *DepthmapX* to study how people see and interact in the space. This method helps designers predict how people will see and connect, and make better design choices based on the layout. Although the study focuses only on flat tree layouts and spacing, it is still helpful in the early design stage for comparing different shapes. More research is needed to look at the effects of tree canopies in three dimensions. The findings highlight how important trees are for shaping what people see in city parks. The results show that curved, free-form planting patterns and central gathering areas help create more connection and flow. As a result, these techniques are a good way to improve planting designs and predict how people will move and interact before they are put into practice.

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Development of a Data Model for Lossless Exchange of Data in Landscape Planning – The Example of XPlanung

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Abstract: The XPlanung standard provides Germany with a technical data model and an exchange format (XPlanGML) that can be used for spatial planning, regional planning, urban land-use planning, and landscape planning. An examination of version 5.3 has revealed that further development is needed to fully map landscape planning projects. This was carried out as part of a project funded by the Federal Agency for Nature Conservation. The results were implemented in version 6.x and existing software systems. Practical tests have shown that the developed technical model can be used and integrated into GI systems. Furthermore, these standardized geodata provide an important source of information for BIM processes. However, the subject models currently in use differ, which will require the definition of transformation rules in the future. The further development of the landscape planning domain model and the legal basis for using the standard have created the conditions for accelerating planning processes in the future, improving the supply of information in BIM processes, and supporting the automated evaluation of plans and the development of domain applications.

Keywords: Landscape planning, data exchange, standardization

1 Introduction

Landscape planning provides comprehensive environmental information at various levels of detail for individual planning levels. It makes use of existing geospatial and geospatial reference data at the federal and state levels, which is provided by existing geospatial data infrastructures (BILO 2015). At the same time, landscape planning itself generates environmental information that is used for its own specialist tasks, in the context of environmental assessments (e. g., environmental impact assessments), by other specialist planning departments (e. g., water management), or for integration into overall spatial planning (SCHULTZE & BUHMANN 2008) or for BIM-projects (CARSTENS 2019, GNÄDINGER & ROTH 2021, GNÄDINGER 2023). This means that the geodatasets generated in the landscape planning process can be seen as the core of an environmental information system and can even replace it at the local level (BFN 2012). It is fundamentally possible to make the data created by landscape planning available on a platform-independent basis and to exchange it between different systems through the use of suitable information and communication technologies. This means that it can be used to address various environmental issues (e. g., developing land pool solutions) regardless of location or time (PIETSCH 2018). In practice, different software systems are used for this purpose. If data is to be exchanged between these systems within planning processes, data format conversions are often necessary, which can lead to information loss. This makes it difficult to reuse data once it has been collected and to exploit potential synergies (ARNOLD et al. 2005). To ensure lossless data exchange across different media and software, so-called subject data and object models can be used (PIETSCH & Heins 2009, MÜLLER

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& WÜRRIEHAUSEN 2013). Since landscape planning is not regulated uniformly across Germany, this poses a challenge for the derivation of a data model (JEDICKE et al. 2016). The XPlanung standardization project, along with many other initiatives (e. g., XBau, Building Information Modeling (BIM), CityGML, OKSTRA©), defines technological specifications that are relevant to landscape planning in Germany. At the same time, practitioners are calling for the provision of standardized plan symbols and standardized data/information. Among other things, this is intended to avoid media discontinuity, improve communication in the planning process, and simplify the consolidation of different planning statuses.

However, a review of version 5.3 showed that it was not suitable for fully mapping landscape planning plans. This means, among other things, that it is not possible to map the addressee reference, the multifunctionality of areas, or the analysis, evaluation, conflict and target plans in landscape planning. For this reason, further development of the technical model was necessary (SCHLAUGAT et al. 2023). Table 1 shows a comparison of the contents of the versions.

Table 1: Comparison of the contents of different versions of the XPlanung standard with regard to landscape planning

	Version 5.3	**Version 6.x**	**Version 7.x**
Content	Core model for landscape planning according to plan symbols from 2000	Core model for landscape planning according to § 9 BNatschG without analysis, evaluation, conflict and goals including addressee reference and multifunctionality	Complete subject model including analysis, evaluation, conflict, measures, addressee reference and multifunctionality
Referencing	None	Referencing content to the technical model for urban land-use planning and regional planning	Referencing content to the technical model for urban land-use planning and regional planning

This article shows how the technical model for the standard was developed, what results have been achieved, and how these have been implemented. It also briefly describes how the standard relates to BIM, as well as its added value and potential future uses.

2 XPlanung

XPlanung is a nationwide uniform data standard for mapping spatial planning, state and regional planning, urban land-use planning, and landscape planning in Germany (BENNER et al. 2008, LEITSTELLE XPLANUNG/XBAU 2020). The aim is to enable the lossless exchange of information between different actors and software solutions. As a communication interface for processes in the construction and planning sector, XPlanung is an essential prerequisite for ensuring that landscape planning issues, among other things, are considered in digital processes (TAIBER 2025).

2.1 Origin and Mandatory Introduction in Germany

XPlanung is based on the fundamental principles of e-government and is designed to support and accelerate electronic data processing in administrative procedures (BMWI 2006). In addition, XPlanung is a standardized technical model for the uniform storage and description of planning information. As early as 2002, the need for a data standard for spatial instruments in municipal planning in Germany was identified (BMWI 2006). For this reason, models were developed which were continuously adapted over time and published in different versions. These form the basis for the development of software solutions for using the standard.

In 2011, the standard was assigned to the IT Planning Council, which records nationwide standardization requirements and specifies their scheduled implementation within a standardization agenda (KoSIT 2014). As a result, the definition of requirements specified that manufacturer-independent, lossless data exchange must be enabled for procedures in the construction and planning sector (IT PLANUNGSRAT 2016). By February 2023 at the latest, IT procedures in the construction and planning administrations of local authorities must be able to process XPlanung-compliant data and message objects. A distinction must be made between the two recording methods: partial vector and full vector. Partial vector refers to the recording of the scope of the respective plan as an outline and all associated plan drawings as a georeferenced raster plan, with additional documents to be attached. In full vector recording, all geometries and sub-elements, including their textual provisions, are recorded in the data standard, resulting in homogeneous and evaluable data sets. This provides a legal basis for the use of the standard in Germany.

2.2 Data Model Design and Structure

The XPlanung data standard is based on Extensible Markup Language (XML). XPlanung uses Geography Markup Language (GML), which is based on XML, to map spatial objects (*features*) and their geometry (TAIBER 2025). This distinguishes XPlanung from other standardization initiatives such as Building Information Modeling (BIM).

The XML schemas have a modular structure, which allows for flexible and expandable use. Class diagrams (UML) show the classes and their structure in the **object model** (Fig. 3). Model areas summarize technical planning disciplines or plan types (e. g., landscape planning). **Object areas** bundle certain technically related classes and other UML elements into a package (e. g., landscape planning measures). **Abstract classes** define general properties that can be shared by derived classes (e. g., the class *LP_GeometryObject*, which describes the attribute position). **Instantiable classes** can then be derived from these abstract classes, which "inherit" the properties of the parent classes and in which concrete objects can be created (e. g., tree). In UML, different characteristics are represented in so-called **enumeration lists** (e. g., different biotope types). Alternatively, characteristic lists can be implemented using **external code lists** published in a GDI-DE code list register. Cardinalities indicate the number of relationships that exist:

- 0-1 times (an optional attribute with a maximum of one value)
- 0..n times (an optional attribute; multiple assignments are possible) or
- 1..n times (a mandatory attribute; multiple assignments are possible) (BENNER 2023, PIETSCH et al. 2023).

An example is shown in Figure 1.

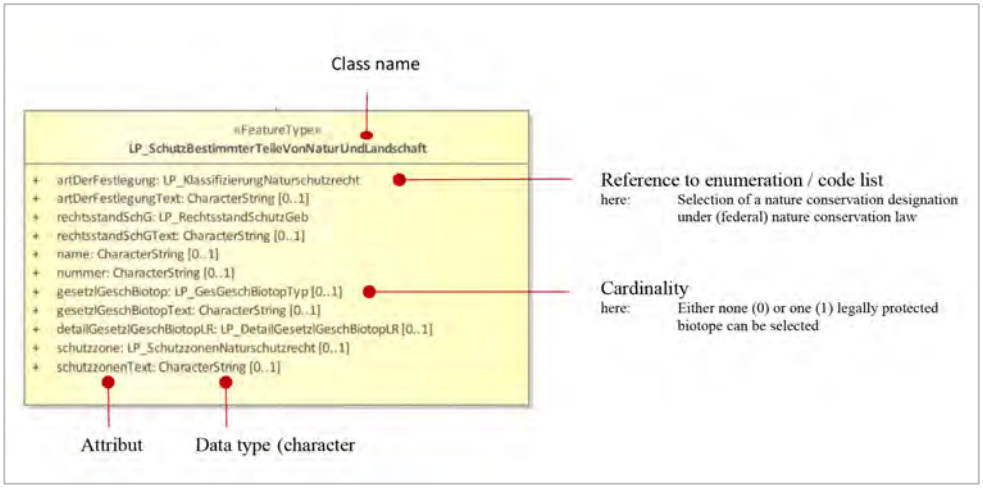

Fig. 1: Description of the contents of an object class using the example of protected areas designated under nature conservation law (BENNER 2025)

When new versions of the standard are developed, it must be checked whether transformation rules need to be defined to ensure that data from older versions can be transferred to the updated version. These serve as the basis for software development and the necessary transformation processes for existing data.

2.3 XPlanung for Landscape Planning

The Leistelle XPlanung/XBau in Germany provides and maintains specialist models for all of the aforementioned planning documents (section 2). However, an examination of version 5.3 of the standard revealed that it is not sufficient to fully represent the contents of a landscape planning plan and thus meet the requirements of media-break-free data exchange (Leistelle XPlanung/XBau 2020). For this reason, the Federal Agency for Nature Conservation awarded a research contract to further develop the standard for use in landscape planning.

3 Procedure for Developing a Data Model for Landscape Planning

A multi-stage process was developed to determine the need for expansion of the standard (Fig. 2). The first step was to examine which plans (landscape program, landscape framework plan, landscape plan, green space plan) and which specific contents could be processed. These resulted in a stage model. Subsequently, the core content of landscape planning was derived on the basis of a multi-stage data analysis. This was done on the basis of legal and technical requirements, the analysis of a selection of representative sample plans, and discussion and evaluation with a panel of experts. From this, a proposal for an extension of the technical data model was developed, which was then subjected to a practical test. The resulting need for adjustments was determined and the final draft was developed in consultation

with the expert committee. This was handed over to the Leitstelle XPlanung/XBau and ultimately resulted in version 6.0, which was published in 2022.

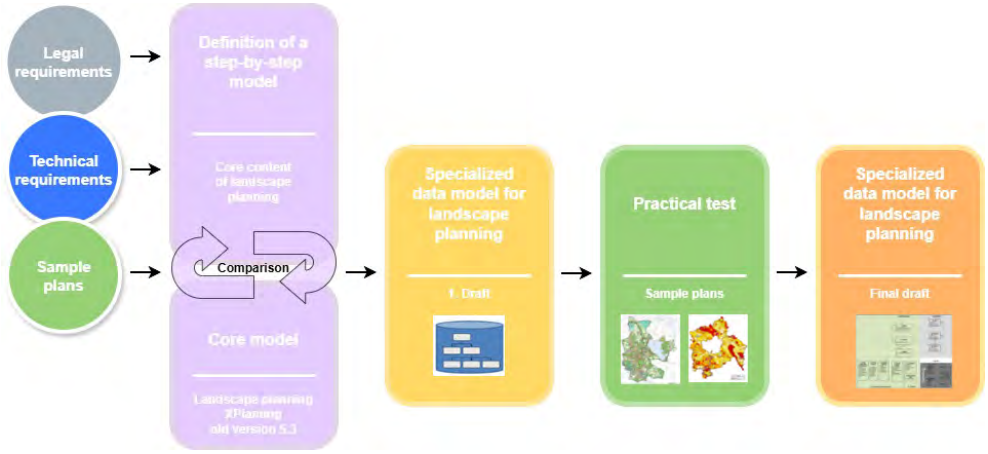

Fig. 2: Procedure for developing a proposal for expanding the core landscape planning model (PIETSCH et al. 2023)

Since this meant that "only" the core content could be displayed (chapter 4), work has been underway since 2022 in a further project by the Federal Agency for Nature Conservation to supplement the missing content. The results will then be integrated into version 7.0 of the standard. This process is not yet complete.

4 Result of Version 6.x

As a result of the analysis, specific core content was defined in accordance with the legal norm of section 9 (2) BNatSchG, in particular the concrete objectives of nature conservation and landscape management, as well as the requirements and measures necessary for their implementation. To this end, three higher-level object classes were defined for the landscape planning model: *LP_Plan* (e. g., content relating to the type of plan, such as a landscape plan), *LP_Area* (further specification, e. g., to individual sub-maps such as the development map), and *LP_Object* (e. g., statements on legal status or integration into other specialist planning). Four technical object classes represent the areas of objectives, requirements, and measures for nature conservation and landscape management, protected areas under nature conservation law, biotope networks, and impact regulation. The class *LP_ZieleErfordernisseMassnahmen* bundles the core content of landscape planning. The UML diagrams are shown in Figure 3.

Fig. 3: UML diagrams of the landscape planning domain model (BENNER 2025)

This ensures that all essential content can be captured, stored, and exchanged in full vector format.

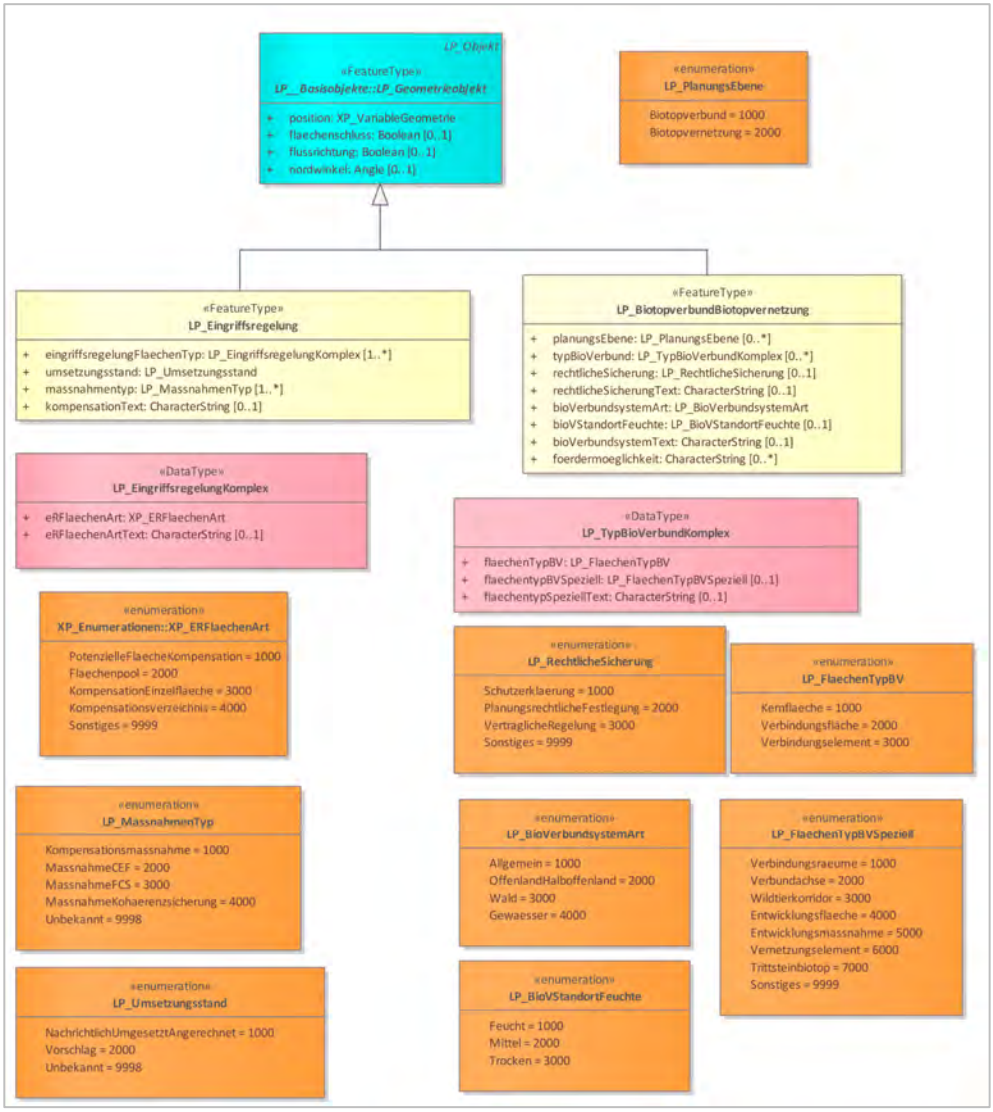

Fig. 4: UML diagrams of LP_PlaninhalteLandschaftsplanung (BENNER 2025)

Figure 4 shows the UML diagram of *LP_PlaninhalteLandschaftsplanung* with the respective enumeration lists, the relations to the geometry objects, individual attributes, data types, and cardinalities.

From version 6.x onwards, it is possible to prepare landscape planning statements on an address-based basis. This ensures that the database already shows who the landscape planning statements are aimed at, as these requirements are formulated for nature conservation authorities as well as many other specialist authorities such as water management, forestry, agricul-

ture, or urban planning authorities. Another important aspect is the possibility of multifunctional planning statements. Many landscape planning objectives and measures can have an impact on different protected resources. For example, planting a hedge has positive effects on biodiversity, can store CO_2, and minimize wind and water erosion.

Another important innovation is the modeling of integration possibilities into spatial and urban planning. In Germany, there are different forms of integration. As part of a weighing process, the statements of municipal landscape planning are transferred to the categories specified in the Building Code. To support this process and make it more effective, it is now possible to reference objects directly within the specialist model between object classes of landscape planning and spatial and urban land-use planning. This can support future adoption and thus exchange at the various planning levels. A similar approach was chosen for objects within the landscape planning specialist model. For example, arable land that is to be converted into grassland (measure) can simultaneously function as part of a biotope network corridor.

By defining cardinalities and enumeration lists, it is possible to standardize the content of landscape planning. In particular, the definition of mandatory attributes ensures the quality of data sets. However, further coordination will be necessary in the future, as the content presentation and technical processing of landscape planning in Germany has not yet been standardized.

The version has now been implemented in existing software systems that support the standard and is available for users to apply in practice.

5 Testing the Usability of the Standard in Practice

Two existing plan examples were selected to test their practical usability. These were the Cottbus landscape plan and the Hameln-Pyrmont landscape framework plan (Fig. 5). The test focused on the following questions:

- Which class can be used to capture the content presented in each plan?
- Can all subject content be captured using the defined attributes and enumerations, or what additions are needed in the model design?
- Can the content be represented sufficiently concretely using the enumeration lists that have been created?
- Are there any attributes or relations missing for mapping the existing plan content?

The assignments were presented in tabular form and unclear or missing assignment options were identified. Since the geodata was available for both plans, it was possible to check the transfer to the standard. The results showed that the necessary classes were available for all content in the sample plans (question 1). With a few exceptions, all objects could be fully mapped with the defined attributes and enumerations (question 2). There were uncertainties in the assignment of the enumeration lists for the attributes “right character” and “spatial concretization,” so both attributes were presented and discussed in detail at the third expert workshop. As a result, additions were made. Additions were also necessary with regard to spatial concretization (spatially concrete representation of plan contents). The content (question 3) could also be transferred in sufficient detail. Furthermore, it was found that no attributes or relations were missing (question 4). In addition, the data model design was imple-

mented in existing GI systems from a technical perspective. The results showed that the implementation of very extensive enumeration lists in geodatabases and GI systems in particular posed a major challenge. The subsequent preparation of plans can lead to room for interpretation, as in some cases it is not possible to clearly derive the specific spatial characteristics of some plan content (e. g., air corridors, habitat corridors). In principle, all content could be mapped completely. It was also possible to implement multifunctional aspects and addressee references in the geodata, which had not been possible previously.

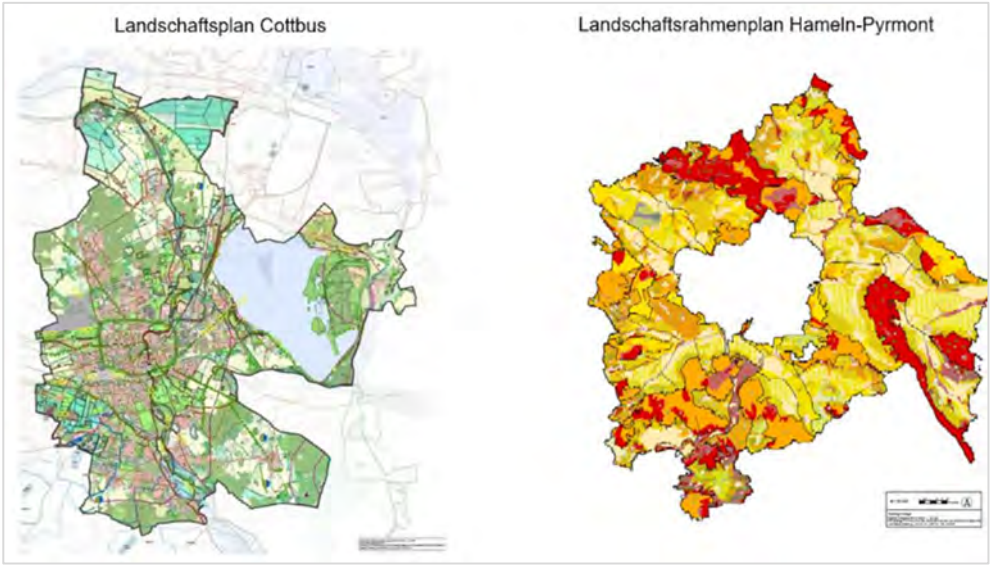

Fig. 5: Selected sample plans for the practical test (City of Cottbus 2016, Hameln-Pyrmont district 2001)

6 Relationship Between XPlanung and BIM

As mentioned at the outset, the XPlanung standard was developed for spatial planning, state and regional planning, urban land-use planning, and landscape planning, while the building information modeling (BIM) method is used in the planning sector to map the life cycle of construction projects. In terms of landscape planning, the specialist scheme in XPlanung forms the basis for what is known as precautionary landscape planning, which is usually carried out across an entire state, region, city/municipality, or parts of a municipality. There are various specialist models for BIM processes that include project-related landscape planning and its instruments, such as the FFH compatibility assessment, the environmental impact assessment, the landscape conservation accompanying plan, or the landscape conservation implementation plan. These culminate in a digital twin and ensure the supply of information for the entire process of planning, implementation, and operation (CARSTENS 2019, GNÄDINGER & ROTH 2021, GNÄDINGER 2023). The following table compares the two approaches using Germany as an example.

Table 2: Comparison of the XPlanung standard and the Landscape_OutdoorFacilities domain model from buildingSmart Germany

	XPlanung	**Fachmodell Landschaft_ Freianlage (BIM)**
Status	Version 6.1	Version 2.0
Dimension	2D	3D
Exchange Format	XPlanGML	IFC
Content	Planning tools for precautionary landscape planning	Planning instruments for project-related landscape planning
Organisation	XLeitstelle	buildingSmart Deutschland

This example clearly shows that specialist models are developed and used for different purposes. Nevertheless, there is enormous potential for developing synergies for the provision of information in the planning processes to be mapped. In BIM processes, data compiled in the context of landscape planning can be used as an important source of information. For example, areas for compensation measures are required when working on road construction projects. As part of municipal landscape planning, area scenarios are developed that can be used as a basis for the BIM process. These can currently be found with the corresponding attributes in the class *LP_ZieleErfordenrisseMassnahmen*. However, a comparison of the two specialist models has shown that the attributes of the measures and their structure currently differ in the two specialist models. For this reason, transformation rules must be defined that enable the integration of data from the XPlanung standard into BIM processes. To this end, pilot projects are currently being carried out in Germany to ensure the integration of data sets in the future.

7 Discussion

With the landscape planning model in the XPlanung standard in version 6.x and its implementation in existing software systems, it will be possible in the future to ensure lossless data exchange between different software systems. However, not all content and maps (e. g., soil, climate/air, water) can currently be displayed. These can only be displayed partially vectorially in the standard. Current work on expanding the specialist model should close this gap from version 7.x onwards.

During the development of the domain model, particularly in discussions with the expert committee, it became apparent that the high degree of abstraction in the standard made discussion difficult. For this reason, it was necessary to provide extensive training for those involved in order to establish a uniform understanding and work on development in a targeted manner. Another challenge is the lack of technical standardization and up-to-date plan symbols for the further development of the technical model. This led to comprehension problems during coordination and required a more complex representation of the technical content within the standard. The different methodological approaches used in practice and the integration models for landscape planning into overall spatial planning also made modeling more difficult. For this reason, the option of specifying text fields was made available for a large amount of content. Although this ensures that all conceivable content can be mapped, it complicates the automated evaluation of the geodata generated. For this reason, it would be de-

sirable in the future to develop a kind of “minimum standard” for landscape planning content among experts in order to ensure the maintenance and further development of the standard.

Even though the technical requirements have been pointed out, the current version of the standard and the XPlanGML exchange format provide an important building block for the seamless exchange of geodata in a horizontal perspective (between landscape planning and overall spatial planning) and in a vertical perspective (between the planning levels of landscape planning). This offers the possibility of automated evaluation of existing plans at different administrative levels and the derivation of specialist applications (e. g., compensation cadastre). Web-based information systems can be developed using the geodata. This is another important building block in the use of standardized, quality-tested data in other planning or decision-making processes. This will provide another important source of information for BIM processes in particular in the future. However, initial tests have shown that the specialist models need to be checked and that suitable transformation rules need to be developed. This should be tested in further pilot projects and for different use cases in order to further increase the usability of the data, which is costly to generate.

It can be assumed that the provision of standard-compliant data will accelerate planning, participation, and approval processes in the future. However, to achieve this, it must be ensured that the developed specialist models are continuously maintained and adapted to current requirements.

In addition to providing technical solutions and maintaining the domain model, another important factor in increasing acceptance and use in practice is informing and training users, especially planners. The use of the standard changes the way geodata is generated. This has a direct impact on the development of the respective plans and must be integrated into the processes of the offices. The same applies to the commissioning administrations, which must also familiarize themselves with the application of the standard. This requires the definition of responsibilities, quality control of generated data, and the adaptation of processes.

8 Conclusion

Work is currently underway to expand the standard to include the missing content for municipal landscape planning and the landscape framework plan. These will be incorporated into version 7.0. This will enable the complete mapping of landscape planning content in the future. Implementing this version in software systems will make it easier for planners and administrations to use. It will be interesting to see how acceptance develops in practice. The experience gained in the further development of the specialist model can be used to contribute to the development of specialist models in other fields or for other processes or planning documents in landscape planning. With the almost comprehensive provision of this standardized data, a number of AI applications and other specialist applications are sure to be developed that will make an important contribution to digitization and accelerating planning.

Acknowledgements

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The Low-Altitude Data Platform: A New Paradigm for Dynamic and Interactive Digital Landscape Architecture

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Abstract: Digital Landscape Architecture (DLA) has achieved increasing representational fidelity through GIS, BIM, and digital twins, yet it remains constrained by a persistent bottleneck: input data is often episodic, low in temporal resolution, and weakly connected to ongoing landscape processes. This paper proposes the concept of a low-altitude data platform as a conceptual framework and methodological agenda that reframes the "digital landscape" from a static model into a live, interactive platform. Enabled by unmanned aerial vehicles and emerging low-altitude mobility, the platform elevates data acquisition into a primary, continuous activity and supports three core capabilities: 4D volumetric sensing for time-dependent ecological and socio-spatial processes; a closed-loop cyber–physical interaction that links sensing, analysis, decision-making, and intervention; and immersive public engagement through dynamic, legible, and participatory interfaces. The paper also argues that the technical promise of such platforms cannot be separated from governance and ethics, prevent monopolization, fragmentation, and surveillance harms. The contribution is a structured foundation for future empirical studies and prototypes that aim to make DLA more responsive, evidence-based, and publicly accountable.

Keywords: Low-altitude economy, digital landscape Architecture, 4D sensing, cyber–physical feedback, platform governance

1 Introduction

Digital Landscape Architecture (DLA) is often described as a trajectory of increasing representational fidelity, data integration, and intelligence – from early Geographic Information System (GIS) mapping and Computer-Aided Design (CAD) modelling, to Building Information Modelling (BIM), and onward to recent digital twin concepts. However, despite these advances, DLA still faces a fundamental bottleneck: its input data is typically gathered episodically, low in temporal resolution, and weakly connected to the landscape's ongoing processes. Many digital landscape models remain intermittently updated "static snapshots," refreshed monthly, annually, or only when a project budget permits; by contrast, landscapes are dynamic systems continuously shaped by weather, management actions, disturbances, and human use. When data collection lacks timeliness and continuity, digital models inevitably lag behind the actual changes unfolding on the ground.

This limitation originates in the dominant data acquisition paradigm. Ground sensors can provide continuous data streams but are fixed in place, limited in coverage, and costly to deploy at scale; manual surveys are episodic by definition; and satellite imagery offers broad coverage but is constrained by revisit frequency, resolution, and atmospheric conditions. As a result, DLA workflows often treat data as a passive by-product of other activities rather than as a continuously updated resource.

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This paper argues that emerging low-altitude technologies – most visibly unmanned aerial vehicles (UAVs) – catalyze a paradigm shift in DLA. The key is not simply that drones provide higher-resolution imagery, but that they enable a mobile, on-demand, and continuous layer of data and interaction. When aerial sensing becomes widely available and routine, the "digital landscape" can evolve from a static model into a live platform: a structured system that continuously ingests multi-source data, maintains an up-to-date representation of the landscape, supports analysis and simulation, and mediates feedback between digital decisions and physical change. In effect, DLA can move from a snapshot paradigm toward a dynamic, feedback-driven paradigm.

Framed as a conceptual foundation rather than a technical implementation, this work highlights three key capabilities the low-altitude data platform unlocks, as well as the governance challenges it entails. First, 4D volumetric sensing (3D + time) allows landscapes to be modeled as evolving processes rather than static forms, enabling time-series interpretations of ecological performance and human use patterns. Second, a closed-loop cyber-physical interaction links sensing, analysis, simulation, decision-making, and physical action into an iterative cycle, allowing continuous adjustments to the landscape at multiple temporal scales. Third, immersive public engagement becomes feasible when the digital landscape is not merely a design artifact but a shared interface that communicates change, uncertainty, and trade-offs in near real time. Crucially, these advances must be accompanied by a hybrid governance framework to ensure the platform serves the public interest, avoiding data monopolies and surveillance harms, while embedding privacy and equity considerations into its design.

2 The Low-Altitude Data Platform: Conceptual Framework and Methodological Agenda

The low-altitude data platform is defined as an integrated system composed of three tightly coupled elements: a mobile sensing layer, a distributed intelligence layer, and an interactive interface layer. The mobile sensing layer refers to UAVs and other low-altitude vehicles equipped with environmental and spatial sensors, which are relocatable, taskable on demand, and scalable for broad spatiotemporal coverage. The distributed intelligence layer consists of databases, analytical pipelines, simulation engines, and AI models that together transform raw sensor inputs into interpretable information – performing functions like time-series analysis, change detection, microclimate simulation, and scenario testing. The interactive interface layer connects this intelligence to designers, managers, decision-makers, and the public, translating complex spatio-temporal data into legible visualizations (maps, dashboards, 3D scenes, immersive environments) and allowing users to explore scenarios, understand uncertainties, and provide feedback. Together, these elements form a platform that is continuously active rather than periodically assembled: data flows are cyclical rather than linear, enabling iterative interpretation and adjustment over time. Fundamentally, this represents a shift from viewing the digital landscape as a discrete model to treating it as a continuously operating platform with real-time feedback.

Conceptually, the platform's architecture can be described as three layers with bidirectional data flows forming a feedback loop (see Figure 1). The sensing layer encompasses UAV-based photogrammetry, LiDAR, thermal imaging, and multispectral sensing as primary data

sources, complemented by ground sensors, satellite data, and crowd-sourced inputs. Rather than serving as a standalone source, the low-altitude layer acts as a coordinating and densifying mechanism that fills temporal and spatial gaps in existing datasets. The intelligence layer receives, stores, and processes the incoming data streams, converting raw observations into structured representations such as time-series point clouds, volumetric change maps, performance indicators, and predictive simulations. Crucially, this layer enables continual model recalibration: as new data arrives, analytical models are iteratively updated, allowing interpretations to evolve rather than remain static. The interface and action layer links analysis back to real-world interventions. Outputs from simulations or performance assessments inform design modifications, maintenance actions, or policy decisions; these actions (e.g. targeted irrigation, access management, or temporary spatial reconfigurations) then alter the physical landscape, which is subsequently re-sensed by the platform. In this way, a cyber-physical feedback loop is created between digital reasoning and material change.

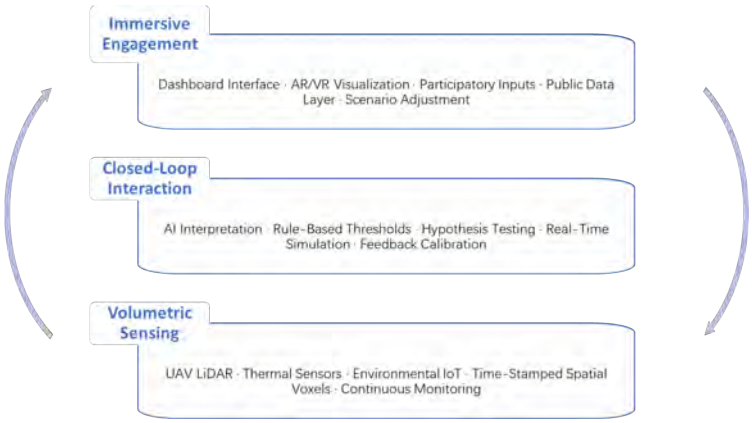

Fig. 1: Layered architecture of the low-altitude data platform

The low-altitude platform also establishes a methodological agenda for DLA, signaling three important shifts in practice. First, evaluation moves from static assessment to process-oriented analysis: by structuring data as time series, landscape performance can be assessed dynamically over time, and design outcomes are judged not only by initial form but by observed behavior through time. Second, models and reality enter a continuous cycle of iterative calibration: predictions and simulations are no longer treated as final outputs but as hypotheses to be tested and refined with each new round of observations, aligning DLA with adaptive management approaches in ecology and infrastructure planning. Third, the role of the landscape architect is reframed: rather than acting solely as the author of a fixed design, the designer becomes a curator of rules, thresholds, and response strategies within a living system. Importantly, this agenda does not imply technological determinism; the platform's analytical power must be matched by deliberate choices about what is measured, how uncertainty is communicated, and who has authority to act on the data. These questions set the stage for the following sections, which detail the platform's three core capabilities (4D sensing, closed-loop interaction, and immersive engagement) and then address the governance and ethical considerations that accompany them.

3 4D Volumetric Sensing and Time-Dependent Landscape Performance

4D volumetric sensing refers to integrating an explicit temporal continuity into 3D landscape models, enabling them to capture dynamic processes over time. Traditional digital landscape models tend to privilege static spatial configurations – treating time implicitly or indirectly – whereas real landscapes are shaped by processes unfolding over time: vegetation growth and stress, microclimatic fluctuations, hydrological dynamics, and changing patterns of human use. Capturing these processes requires not just higher spatial resolution, but a fundamentally different temporal logic driving data collection and model updates.

Low-altitude sensing systems enable this shift by allowing repeated, on-demand data acquisition at frequencies aligned with the landscape's own rhythms. UAV-based photogrammetry, LiDAR, and multispectral sensors can be deployed at intervals dictated by actual landscape changes, rather than by inflexible survey schedules. Structured as time-series point clouds or volumetric datasets within the platform's database, the digital landscape gains temporal depth and can represent change itself rather than just isolated states. In effect, the focus moves from static "form" to dynamic "process": growth, decay, movement, and disturbance become intrinsic dimensions of the model rather than external factors, and the landscape is framed as a continuously evolving system. Notably, this does not imply constant surveillance or indiscriminate data hoarding – the platform supports selective temporality, meaning different processes are monitored at appropriate frequencies. The goal is to align sensing schedules with meaningful landscape processes, rather than to maximize data collection for its own sake.

By providing real performance data over time, 4D sensing supports performance-driven design and adaptive management. In conventional practice, metrics like thermal comfort, solar exposure, or habitat quality are often evaluated via simulations based on assumed scenarios. With continuous monitoring, however, designers can derive performance indicators from observed data streams and iteratively calibrate their models to reflect actual conditions. Design decisions thus shift from fixed solutions to hypotheses that are tested and adjusted through ongoing observation. Over time, this feedback-driven approach leads to more resilient and evidence-based landscape strategies, particularly in contexts characterized by uncertainty and change.

For example, in urban vegetation health monitoring, the platform demonstrates a full data-to-decision feedback loop. Low-altitude multispectral and thermal imaging can detect early indicators of plant stress – subtle changes in spectral reflectance or elevated canopy temperatures – before decline becomes visible to the naked eye. The platform's intelligence layer analyses these warning signals in context with recent weather patterns, irrigation schedules, and soil conditions to pinpoint potential stress factors. Based on these insights, targeted interventions can be taken: adjusting watering regimes, deploying temporary shading, or scheduling pre-emptive maintenance. Subsequent UAV surveys then monitor the effects of these actions, revealing whether vegetation health and microclimate conditions improve. This data-driven closed loop shifts landscape management from reactive to preventive: issues are identified and addressed at an early stage, rather than waiting for visible deterioration and reacting after the fact.

4 The Interactive Feedback Loop: From Digital to Physical

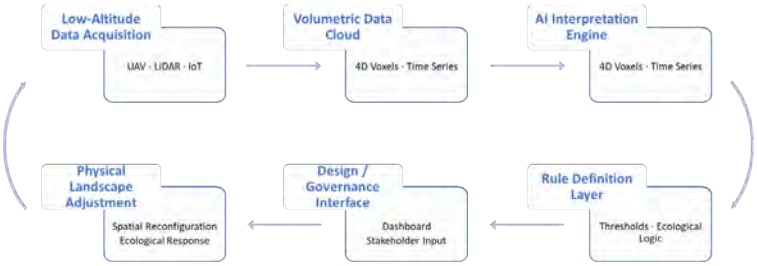

Fig. 2: Closed-loop operational workflow of the platform

The low-altitude platform's most distinctive innovation is the establishment of an interactive feedback loop between the digital model and the physical landscape. This loop functions as the platform's operating system, interlinking sensing, analysis, decision-making, and intervention into a continuous process. In conventional landscape workflows, the sequence from analysis to implementation is largely linear: data are collected, interpreted, and translated into a design proposal which is built, and only after long delays is performance feedback obtained – feedback that typically informs future projects rather than adjusting the one already built. In contrast, the low-altitude platform embeds feedback into everyday landscape operations, closing the once-disconnected steps into an immediate cycle and enabling design and management to be iterative rather than one-off.

This feedback loop can be conceptualized in four repeating stages: sensing, analysis, decision, and intervention. First is sensing, carried out by low-altitude systems that capture high-resolution data whenever conditions warrant, instead of on a fixed schedule. Second is analysis, in which incoming data is processed within the distributed intelligence layer (for example, through change detection, real-time simulation, or performance assessment) to generate provisional insights about the landscape. Third comes decision-making: based on those insights, design or management choices are made – these may be executed automatically, semi-automatically, or through human direction, depending on governance settings and context. The fourth stage is intervention: physical actions are implemented in the landscape (e.g. deploying a temporary drainage pump or adjusting an irrigation schedule), directly altering the site's state. That new state is then captured by the next sensing cycle, closing the loop of feedback. This cycle operates across multiple temporal scales – facilitating rapid responses to acute events as well as gradual adjustments in routine maintenance regimes.

By operating in a closed loop, the platform enables an adaptive approach in which strategies are refined in near-real time as conditions change. The value lies not in perfectly predicting outcomes, but in the capacity to learn and adjust on the fly under uncertainty – improving interventions with each cycle based on observed results. Importantly, human expertise remains integral to the loop: designers and managers must decide what variables to monitor and what thresholds trigger action, interpret the platform's automated outputs, and ensure that interventions align with broader goals and values. Automation can handle routine or urgent responses, but its scope and authority are defined by the governance framework to balance agility with safety and accountability.

5 Immersive Public Engagement and Participatory Interfaces

Reframing the digital landscape as a live platform also transforms how non-expert publics encounter, understand, and participate in landscape decision-making. In the past, public engagement has been mediated through static representations – maps, renderings, or reports – that distill complex processes into simplified outcomes. While ever-greater visual realism can convey design intent, static depictions alone struggle to communicate uncertainty, temporality, and the dynamic trade-offs inherent in landscape systems. The low-altitude platform makes dynamic landscape processes both legible and experientially accessible: by coupling real-time (or near-real-time) data streams with intuitive interfaces, the public can immerse themselves in landscape changes as they unfold. For example, time-animated 3D models, live environmental dashboards, or even immersive virtual reality environments allow users to explore how seasonal cycles, weather events, or management interventions affect landscape conditions over time, and to visually grasp key thresholds and trajectories. This shift from passive representation to lived experience fosters a more nuanced understanding of landscapes as living systems with temporal dynamics and uncertainties, rather than as static blueprints on paper.

Beyond helping the public "read" and witness landscape change, the platform enables a new mode of participation – the public as data contributors. Citizens can supply local observations via distributed sensors, mobile applications, or community reporting, complementing the data collected by drones and official sources. These crowd-sourced contributions are especially valuable for capturing social usage patterns, subjective perceptions of comfort or safety, and fine-grained environmental conditions that aerial sensing might overlook. For example, residents might report localized flooding, odors, or noise levels, providing detail that UAV surveys alone cannot. When integrated into the platform's intelligence layer, such contributions enrich analysis and can reveal gaps between modeled performance and lived experience. Importantly, this participatory dimension requires governance measures to ensure data quality, protect privacy, and maintain equitable representation. Participation should be framed as co-creation rather than one-sided extraction: through collaborative data stewardship, contributors not only provide data but also benefit from the resulting insights and gain influence over decisions that affect their environment.

By making landscape dynamics transparent and broadly accessible, the platform becomes a venue for negotiation and collective learning. Landscape decisions invariably involve trade-offs – flood mitigation might constrain recreational space, or ecological restoration might alter established social uses. The low-altitude platform does not automatically resolve such conflicts, but it offers a shared evidence base for stakeholders to debate options using common facts. With continuously updated information, different parties can observe how various strategies actually perform and, on that basis, discuss trade-offs and adjust objectives. Public engagement shifts from a one-off consultation to an ongoing dialogue: as time progresses, stakeholders collectively learn from real feedback and refine their approaches accordingly. This approach aligns with broader movements in planning toward adaptive governance and knowledge co-production, moving landscape decision-making from an expert-driven process to a multi-party collaborative one. In this way, the digital landscape platform is not only a tool for professional decision-making, but a mediating infrastructure where spatial expertise, public values, and empirical evidence intersect in pursuit of more resilient and inclusive landscape governance.

6 Governance and Ethics of the Low-Altitude Data Platform

Once a low-altitude data platform becomes a routine environmental data infrastructure, its value and risks scale together. On the one hand, it can enhance the timeliness of landscape monitoring, emergency response, and day-to-day maintenance. On the other hand, it can intensify unresolved questions around data rights, privacy intrusion, fragmentation, and unclear responsibility.

The platform ecosystem can be described through three actor groups and the relations among them:

(1) Public agencies and publicly accountable stewards

Their priorities are typically tied to public value – ecosystem monitoring, disaster response, public safety, and infrastructure operations. They often have regulatory authority and public mandates, but also face constraints of transparency, accountability, and resources. For the platform, they may function as providers of baseline standards and as key arbiters of data openness and privacy boundaries.

(2) Commercial operators and service/technology providers

Their incentives tend to be efficiency and commercial value – logistics, inspection, mapping, media services, and the development/maintenance of platform stacks. They often bring rapid iteration and scalable deployment, yet their data practices (collection, retention, reuse) may conflict with public value objectives. In a platform setting, they can become major data producers and, in some cases, de facto infrastructure controllers, raising risks of data concentration and proprietary lock-in.

(3) Civic actors and local stakeholders

Including communities, researchers, and individual users, this group may contribute local observations, articulate needs, scrutinize platform operations, and advocate for public-oriented data use. While they typically lack coercive power, they provide essential checks on equity, accessibility, and contextual relevance – preventing the platform from being driven solely by technical or market logics. At the same time, civic participation introduces practical challenges related to data quality, representativeness, and privacy.

Across these actors, governance can be framed as a set of recurring core tensions – not as a single “solution,” but as trade-offs that platform design and practice must navigate:

Public value vs. proprietary control: To what extent should data and models be open for public decision-making, research, and transparency, while still recognizing private investment and innovation?

Operational utility vs. privacy: What level of granularity is needed for real-time monitoring and closed-loop interventions, and what should be filtered, anonymized, or delayed?

Interoperability vs. pluralism: Common standards reduce fragmentation, but excessive standardization may suppress local variation and innovation pathways.

Automation vs. accountability: When analytics inform action (maintenance, temporary controls, resource allocation), who is responsible for errors, and how can decision chains remain auditable?

7 Conclusion and Outlook

The emergence of low-altitude technologies marks a critical turning point for Digital Landscape Architecture. This paper has argued that their importance lies not primarily in better imagery or greater efficiency, but in the potential to fundamentally transform the "digital landscape" from a static, intermittently updated model into a continuously updating, interactive platform. By elevating data acquisition to a continuous, on-demand process, a low-altitude data platform allows dynamic landscape changes to be captured and analyzed in real time, links digital analysis directly to physical interventions, and broadens the range of stakeholders engaged in landscape stewardship.

4D Volumetric Sensing: Incorporating a temporal dimension into 3D landscape models so that landscapes are represented as evolving processes rather than fixed forms, enabling performance-driven design and adaptive management.

Closed-Loop Interaction: Fusing sensing, analysis, decision-making, and intervention into an iterative feedback cycle between digital models and physical landscapes, so that digital simulations directly inform physical changes and are continuously recalibrated through observation.

Immersive Engagement: Transforming the digital landscape into a shared, legible interface through dynamic and interactive media, allowing the public to understand changes in real time, participate in discussion and decision-making, and collaboratively negotiate landscape strategies.

Governance in this context is not a binary choice but a set of persistent relational tensions – for example, between public value and proprietary control, operational utility and privacy, standardization and local diversity, and automation and accountability. These tensions do not admit a single solution; instead, they define the conditions under which low-altitude data platforms gain legitimacy, remain sustainable, and function as public-facing infrastructures. Accordingly, governance and ethics are framed here not as prescriptive designs, but as analytical dimensions essential for understanding how low-altitude data platforms operate across different institutional and landscape contexts.

Future research should focus on integrating these concepts into working prototypes and empirically testing them across diverse landscape contexts and institutional settings. Challenges such as regulatory constraints, weather dependencies, operational costs, and data biases will need to be addressed through interdisciplinary collaboration and policy innovation. These hurdles do not diminish the transformative potential of low-altitude data platforms; rather, they indicate where further efforts should be directed to make digital landscape architecture more real-time responsive, evidence-based, and collaboratively sustainable.

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Hybrid Terrain Modeling: A Multidimensional Landscape Design Method

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Abstract: This paper focuses on how, in the wake of shifting hydro-topographic regimes in Switzerland, digital design methods can be combined with tactile modeling methods to support the overall design process and output. Bridging crucial gaps in the workflow from geodata to physical modeling the paper proposes a design process which iterates between the realms of the digital and the analog. This approach combines the precision and objectivity of geospatial data with the intuitive working modes and tactile interaction with materiality by introducing a custom Grasshopper plug-in. The paper presents methods tested by students of architecture and landscape architecture, allowing to show different levels of complexity within the method from the digital model to the physical and back to the digital for fully circular iterations.

Keywords: Hybrid design methods, hydro-topography, LiDAR Geodata, Rhino Grasshopper, 3D printing

1 Introduction

The shifting climatic circumstances and water cycles in Switzerland and beyond call for a shift in dealing with water flows, topography and the landscape in general (VOSER 2024). Landscape dynamics are becoming increasingly frequent and pronounced, creating a conflict with the predominantly static landscape infrastructures constructed over the past two centuries (BAN et al. 2020, JACQUEMART et al. 2024, SCHERRER et al. 2016). Over the past decades, engineering disciplines have been leading water management projects in Switzerland and across Europe. It could be argued that landscape architects and their more holistic view should once again assume a more central role in these works (SALLIOU et al. 2025). In order to achieve this, the role of the landscape architect needs to be reconsidered. We argue for a discipline empowered with the means and agency to deliver spaces that allow for natural dynamics whilst integrating social and ecological dimensions all founded on quantitative data. Salliou et al. note that digital models can improve the "hydro-socio-ecological" dialogue for water systems by allowing for precise digital modelling. As implicit in this wording an exclusive focus on digital data and computational methods, their prioritization of objectivity and precision can result in a detachment between the designer and the landscape to design (RAMIREZ & OLÓRIZ SANJUÁN 2016) or as Pallasmaa puts it: "Design is not merely a rational, technical and performative task" (PALLASMAA 1996). Digital tools are most effective when combined with complementary methods and their intended use made explicit (FRICKER et al. 2013, 2024). As other studies show digital-physical combinations can lead to successful design processes if used to their specific advancement (HARMON et al. 2016). This paper will make a case for design methods on the fringes of the digital and the haptic.

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2 A Method for Hybrid Design

2.1 Related Works

We propose a hybrid design approach that combines digital and physical modelling methods – allowing for effective translations between multiple forms of representation, model interaction and design methods. Building on prior tangible-digital terrain studies and Rhino-based hydro-analysis, our contribution refines the balance between precision and iteration speed, allowing for meaningful geometric fidelity and rapid iterations. Both being essential when addressing the challenges of designing dynamic, evolving landscapes. The work relates to studies of AR-Sandboxes (HERMANSDORFER et al. 2020) or the Sedimaschine (CANTRELL & HOLZMAN 2014) which provide live feedback at relatively low fidelity as well as to studies on rapid prototyping with Sand (ROBINSON 2014) or CNC Milling (GIROT et al. 2010) which allow high fidelity but require time-intensive iteration loops and extended technical knowledge. In comparison our method is characterized by a low-entry barrier and haptic modelling techniques. Basing our method on the raw LiDAR data, not relying on translations to rasterized or vectorized data, continues a culture of "Cloudism" (GIROT 2018). Against this backdrop, we ask: How can low-barrier workflows leverage high-resolution geodata, interoperate with existing tools, and be combined with tactile terrain modeling methods to support early-stage topographic and hydrologic landscape design? What benefits and trade-offs do such a workflow entail, particularly in geometric precision, iteration speed, time investment, and the ability to explore design variants, while enabling an intuitive, multisensory engagement with terrain?

2.2 Geodata as a Basis

In a time where hydraulic amplitudes are increasingly shaping landscape design decisions, basing any design on objective georeferenced data is gaining greater importance. The Federal Office of Topography (Swisstopo) has been using LiDAR technology for creating topographic models (DTM) for the past 25 years but only since 2025, high-resolution geodata (classified point clouds with at least 5 points/m², on average around 15-20 points/m², positional accuracy: ±20 cm, vertical accuracy: ±10 cm) have been made available across the entire territory of Switzerland (SWISSTOPO 2025). Despite the challenging topography, the dataset has one of the highest nationwide precisions in Europe (KAKOULAKI et al. 2021). Datasets as point clouds and their subsequent products like rasterized DEM/DTM or vectorized building datasets have become a standard for open government data in Switzerland and beyond. The uninterrupted coverage, high accuracy, and resolution enable designs to be based on geodata at all locations and even at small scales. Data from GIS-platforms such as Swisstopo in Switzerland come in specific formats, which are not directly compatible with design software in landscape architecture and often require various levels of translation before being interoperable. Even though efforts have been made to standardize national geodata across Europe, different formats continue to exist (KAKOULAKI et al. 2021). The three key issues are (1) the translation between different data structures: 3D point data, vector formats, mesh surface or solids, (2) the conversion of a given reference coordinate system to a local origin point and (3) the management of large volume datasets.

2.3 An Accessible Iterative Approach

To establish a design method capable of dealing with today's challenges of hydraulic shifts, we propose a hybrid approach that unites the precision and objectivity of digital data with tactile, hands-on methodologies. The method therefore asks for workflows from geodata to physical models which, due to the mentioned challenges of differing data structures, data volumes and georeference, require advanced software or programming skills by the designer and are not suitable for iterative loops. We introduce a low-barrier, closed digital-physical-digital workflow, operationalized with a specifically developed Grasshopper plug-in (MURMELI 2025) that natively ingests national LiDAR data, 3D-prints negative formworks, enabling rapid sand/clay re-casting (5-10 min/variant) and re-scans for quantitative hydro-topographic analysis, supporting early-stage landscape design and teaching at scale (Fig. 1).

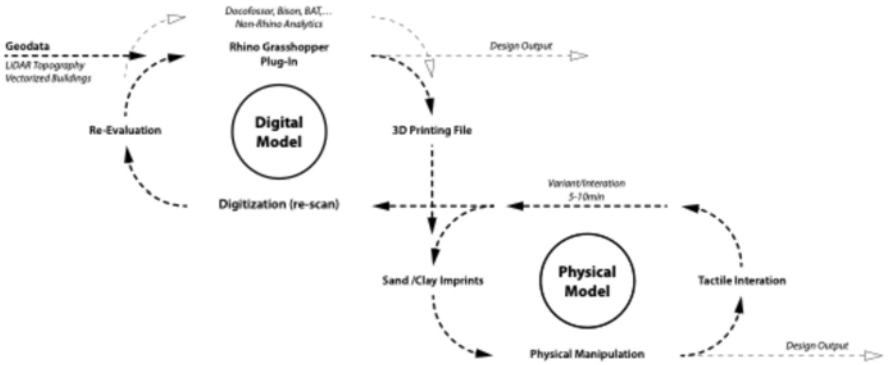

Fig. 1: Method Diagram (digital-physical-digital Workflow) (Image Credits by the Authors)

The custom Grasshopper plug-in was specifically developed to bridge these technical gaps and allows for rethinking hybrid design iteration processes. The components consist of four categories: Importers, Tools, Analysis and Exporters. (Fig. 2) Specific import nodes are programmed to import .las, .laz and .xyz LiDAR files as well as .dxf vector-files utilizing Python 2 for Rhino 7, Ironpython and Python 3 for Rhino 8. The importers include point sampling and classification filters. This increases import efficiency and allows for larger datasets to be imported in both small or large scales.

Fig. 2: Toolbar Rhino Grasshopper plug-in (MURMELI 2025)

The importers allow for bringing the public data into Rhinoceros and leverage existing tools like Docofossor (HURKXKENS & BERNHARD 2019), Bison (BISON 2018), BAT (MA 2024) and many more to investigate watersheds, water runoff or other hydro-topographic characteristics. For the specific workflow of 3D printing custom tools (section 2) were programmed: Point combiner, Point thinner, Shift, Local Z-max, Local Z-min as well as an interface to docofosser's specific distance field format. For topographic and hydrologic analysis section 3 provides eight widely used analyses natively in the plug-in. Further a custom exporter for .stl-files is provided to complete workflows for 3D printing. In combination with standard Grasshopper components the developed plugin supports workflows from geodata download to 3D print file exports. The plug-in is conceived as open access and can be continuously extended with specific tools based on emerging needs during design applications.

3 Design Iterations between the Physical and the Digital

In the following design applications, the models were printed with PLA filament both as positives as well as negative formworks. The latter allows for casting the positive topography creating pressed sand or clay models, which later can be physically manipulated. It allows for conceptual models in large scales and manual sketching in the physical model as well as more detailed hydro-topographic investigations in smaller scales. A new imprint of a sand model with an existing formwork is possible within five to ten minutes which makes it possible to not only work iteratively but also in variants, exploring different time scales, erosion processes and hydrological variabilities. This massively decreases physical model making times and creates repeatable precise outputs. 3D printers with PLA filament commonly have a resolution of ~0.2 mm in height and this precision is replicated on the sand imprints, allowing for details of up to 5 m in models of 1:25'000 and accordingly up to 20 cm in the scale of 1:1'000 or 10 cm in 1:500. (Fig. 3.1) The method was applied in a graduate design studio in landscape architecture (Spring 2025) and undergraduate design studio in architecture (Fall 2025) at the ETH Zurich. In the architecture program, more than 300 students were introduced to topography and hydrology through this method of hybrid modelling, whereas in the landscape architecture program, discourse and form-finding processes using both digital and physical modelling techniques were explored in greater depth allowing for more complex design processes.

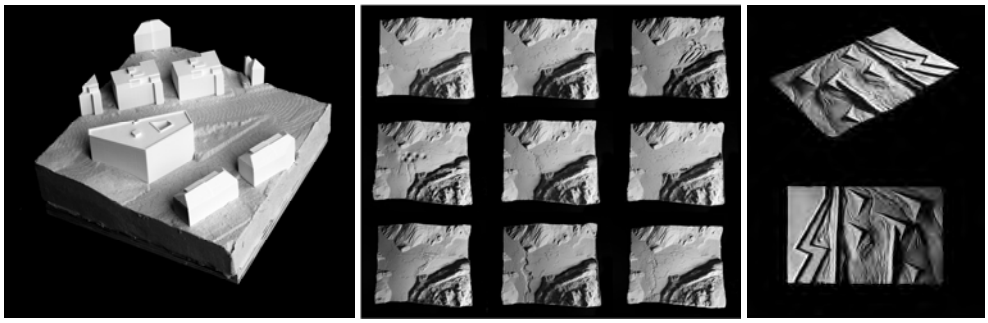

Fig. 3: Left: Inner City Model 1:500 by Lorethan N.; Middle: Concept Models 1:25'000, collective student works; Right: Flow Channels 1:200 by T.-W. Chen & Y. Hou

Starting with large scale conceptual models, the method allowed to sketch even unscaled design ideas (Fig. 3.2). Later smaller scales and more precise intervention modelling, manually shaping the model and digitally deforming the topography before printing a model (Fig. 3.3). The back and forth between digital and physical interventions requires rescanning physical models and juxtaposing the original topography and the manually shaped models. To do so, different strategies were chosen to digitize the physical models. These included laser scanning (GOM Scanner, Artec Leo), photogrammetry and depth-cameras. The latter lacked precision, while hand-held scanners and image-based photogrammetry became the preferable methods. Using these techniques, manual work can be re-evaluated through digital analysis like slope orientation or steepness, water runoff or earthwork volumes (Fig. 4.1, Fig. 4.2). A full end-to-end cycle (3D-printed formwork from geodata, pressed sand-model, and rescanned with a GOM scanner) resulted in a standard deviation of ±0.1654mm in the 1:3000 scale model, equivalent to ±0.4962m at full scale (Fig. 4.3). Models in scales of 1:1000 or larger have an equivalent real-world error of ±0.2m and less, which is comparable to the vertical precision of the source geodata.

Fig. 4: Left: Mixed Models: rescanned physical Model juxtaposed with digital LiDAR Model, Scale 1:25'000, Design Studio 2025; Middle: Slope Steepness Analysis on rescanned physical Model, Scale 1:1'000, by Lang A., Lepori L.; Right: Deviation Analysis after full circle process: geodata/physical model/re-digitization with a standard deviation of ±0.1654mm at a scale of 1:3'000

4 Discussion and Conclusions

Overall, the project shows how condensed workflows in combination with the developed Rhino Grasshopper plug-in allow for design processes with quicker physical modelling that supports more iterative design loops. The proposed method differentiates itself with higher accuracy than other methods due to a haptic focus like tangible tables that allows for more physical interaction and quicker iterations than other precise modelling methods like CNC milling. Despite this carefully tuned balance between precision, haptic experience and time investment, limitations to the methods became apparent during the design applications. 3D printer dimensions limit the size of the model size unless the model is divided and reconfigured into multiple tiles (Fig. 5.3). Initial 3D printing times can reach 10 hours and more per model (25 cm x 25 cm). Consequently, the method is particularly beneficial when existing formwork can be used repeatedly for variants, iterations or group works. The manual intervention has some limitations. Even though providing for characteristic geometries and the haptic experience of the designer manual techniques have limitations in resolution and precision. Especially at large scales, manual modelling is limited to conceptual schemes and exaggerated features. In terms of materiality, the case studies have used kinetic sand, clay

and plaster for their possibility to work on manually. An interesting next step could be to work with site specific material mixtures. Throughout the case studies it became apparent that the presence and the workings of a given topography have much more impact on the design process when physically present in space. Manual manipulation, even if conceptual or out of scale enhances the interaction with the topography. The case study with the more advanced students showed that the back and forth from a digital to an analog realm provides a more multifaceted insight and understanding and allows combining digital analysis tools while circumnavigating the rigidity of purely computational design methods. By breaking these rigid frameworks through unintentional and intuitive modelling, a productive tension between the precise and the intuitive emerges and is revealed in the juxtapositions.

In summary, the method proved to have many applications from early-stage design to final representational models. Allowing students to design in the physical model while keeping efficient work iterations both for advanced master students in landscape architecture as well as previously untrained students of architecture suggests a wide pallet of applications for different stakeholder groups and proficiency levels. Such design processes can lead to better insights in site-specific topographies, faster understanding and communication of topographic and hydrologic specificities as well as more freedom in designing "by hand". While remaining connected to the precision of geodata, the methods engage the designer directly with materiality, connecting them back to the physicality of landscape and allowing, in Pallasmaa's words, the use of *"[...] our magnificent, multisensory, simultaneous and synchronic capacities of imagination"* (PALLASMAA 1996, 5). This allows users to not only address today's hydro-topographic challenges with digital tools, but also through tangible imaginations and physical variants of changing topographies.

Fig. 5: Left: Students working by hand, Spring Semester 2025; Middle: Tools for manual modelling; Right: Multiple tiles combined to one formwork – sand model pressing (Image Credits: Silvia Converso and the Authors)

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Urban Transformation Between Built and Natural Systems by Means of an Adapted Wave Function Collapse Approach

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Abstract: In practice, urban transformation is often carried out at the outskirts or in between existing areas of a city. In that context, important questions are: How can one imagine a transition between different urban structures? What if, additionally, we aim for including not only the development from innermost to outermost but also vice versa – letting nature into the city rather than the other way around? What are the implications of interventions on the surroundings? Addressing these questions requires a modelling approach that links local morphological compatibility between urban structures with macro-scale socio-economic feedback driving development, vacancy and ecological change. To that end, we combine complementary modelling components. A cellular-automaton (CA) grid provides the spatial representation and hosts rule-based land-use transitions over time. Within this structure, an adapted Wave Function Collapse (WFC) operator infers context-sensitive land-use changes from learned adjacency relations, ensuring morphological compatibility of infill and transformation. A system-dynamics (SD) layer generates macro-scale pressures in households, jobs and capital that drive development, vacancy and decline across the grid. Evolution over time emerges from the CA rule system and from vacancy-driven transformations derived from previous work on urban cell grammars, extending WFC from a static pattern generator to a dynamic operator of urban change. Our framework is intended for use in planning, but also in education and policy making ("What-If"-Scenarios). The system supports both conventional development trajectories and their inversion: not only densification and infill, but also decline, abandonment, and ecological succession where nature re-enters under conditions of sustained vacancy.

Keywords: Wave Function Collapse, system dynamics, cellular automata, urban transformation, built environment, natural systems, sustainability.

1 Introduction

Urban transformation is increasingly framed as the reconfiguration of coupled built and natural systems. Beyond outward expansion and densification, cities also undergo decline, vacancy and ecological succession, producing bidirectional transitions between constructed and natural regimes. A central challenge is therefore not only how to develop new urban fabric, but how to model the reciprocal dynamics through which built structures adapt, consolidate or give way to ecological processes over time.

This paper presents a computational framework for simulating such dynamics at the scale of large urban areas. The approach combines a data-driven adaptation of the Wave Function Collapse (WFC) algorithm with a system-dynamics (SD) layer and spatial cellular logic. Urban space is represented as a grid of land-use tiles derived from OpenStreetMap data, from which adjacency rules are automatically learned. These rules guide context-sensitive infill and transformation, while socio-economic pressures – household demand, job demand and capital – drive where development, vacancy or decline occur. Ecological succession and

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planned greening operate within the same spatial structure, enabling the simulation of both growth and re-naturalisation trajectories.

The novelty of the work lies not in introducing a new generative algorithm, but in coupling data-driven WFC rule learning with a dynamic socio-economic simulation and vacancy-based spatial transformation. WFC is embedded within a time-stepped framework in which adjacency constraints (learned from OpenStreetMap), economic feedback and ecological processes interact. This shifts WFC from a one-shot pattern generator to an operator of long-term urban change, enabling planning-oriented "what-if" scenarios that integrate densification, decline and green succession within a unified model.

The paper first reviews related work in urban-ecological modelling and generative spatial methods (Section 2). Section 3 presents the modelling framework, including spatial representation, rule extraction, system-dynamics formulation and transformation mechanisms. Section 4 applies the system to the Hirschstetten/Breitenlee area in Vienna. Section 5 discusses strengths, limitations and future extensions, followed by conclusions in Section 6.

2 Background and Related Work

2.1 Urban Transformation as Dialog Between Urban and Natural Systems

Urban transformation is increasingly framed as the evolution of coupled socio-ecological systems operating across multiple scales. Cities function simultaneously as ecological and economic systems whose spatial structures shape and are shaped by flows of energy, matter, capital and population (ALBERTI 2008, PICKETT et al. 2011, BATTY 2013, FORMAN 2014, GRIMM et al. 2017). In this perspective, the built environment is not static but subject to densification, decline, succession and reconfiguration.

Design theory and urban ecology alike emphasize adaptive relationships between built and unbuilt domains, ecological performance, connectivity and resilience (MOSTAFAVI & DOHERTY 2010, CORNER 2006, DELANDA 2016, REED & LISTER 2014, HENSEL 2013, HENSEL & MENGES 2008; AHERN 2011, ANDERSSON et al. 2014, ELMQVIST et al. 2019, COLDING et al. 2013). Empirical studies further document vacancy, abandonment and re-greening as recurring urban processes (HAASE et al. 2014, KABISCH et al. 2016).

Yet most computational models treat socio-economic dynamics and ecological processes separately, either abstracting from spatial morphology or simplifying green systems (WADDELL 2002, WHITE et al. 2015, BATTY 2018). The framework presented here addresses this gap by modelling urban space as interacting built and natural regimes evolving through adjacency constraints and socio-economic feedback.

2.2 Wave Function Collapse, System Dynamics, Cellular Automata and OpenStreetMap

Our urban modelling approach combines several distinct traditions (also refer to Figure 1): Wave Function Collapse (WFC) generates spatially coherent patterns from local adjacency constraints (GUMIN 2016); system dynamics represents aggregate socio-economic stocks and feedbacks such as population, jobs and capital (FORRESTER 1969, BATTY 2013); and cellular automata (CA) derive spatial change from local transition rules on grids (WHITE & ENGELEN

1993, WHITE et al. 2015). OpenStreetMap (OSM) provides empirically grounded data on buildings and land use, enabling adjacency relations to be learned directly from observed urban fabric (HAKLAY & WEBER 2008, BARRON et al. 2014). The novelty of the present work does not lie in inventing a new algorithmic paradigm, but in integrating these approaches into a single dynamic framework: adjacency rules are learned from real urban morphology via OSM, WFC is embedded within a time-stepped simulation, and socio-economic pressures from a system-dynamics layer drive spatial infill, decline and ecological succession. The contribution therefore lies primarily in the coupling of generative constraint-based modelling with demand-driven transformation and planning-oriented scenario exploration, rather than in WFC itself.

3 Urban Transformations Between Urban and Natural Systems

3.1 Spatial Representation and Patch Attributes

The model operates on a regular grid (Web Mercator zoom 17; ~305 × 305 m per tile). That choice is based on computational feasibility and can be changed to a finer resolution if required. Each tile corresponds to a NetLogo patch with a land-use type, housing capacity, job capacity and green potential. Patches track housing and job use, vacancy, vacancy duration, dereliction level and dereliction duration. Prolonged full dereliction converts a patch to barren land and resets capacities.

3.2 Tile Classification from OpenStreetMap

Initial land-use types are derived from OpenStreetMap data aggregated to the grid. Land-use, building, infrastructure and natural features are mapped to model categories (see Table 1). The classified grid serves as the empirical baseline for both simulation and adjacency rule extraction.

3.3 Deriving WFC Adjacency Rules from Observed Tiles

Adjacency statistics are computed from the initial grid. For each land-use type and direction, neighbour probabilities are derived and stored as directional rule tables. During simulation, candidate patches (empty, barren or green and adjacent to built fabric) sample new land-use types using weighted multiplication of neighbour probabilities. This embeds context-sensitive, data-driven infill into the spatial dynamics.

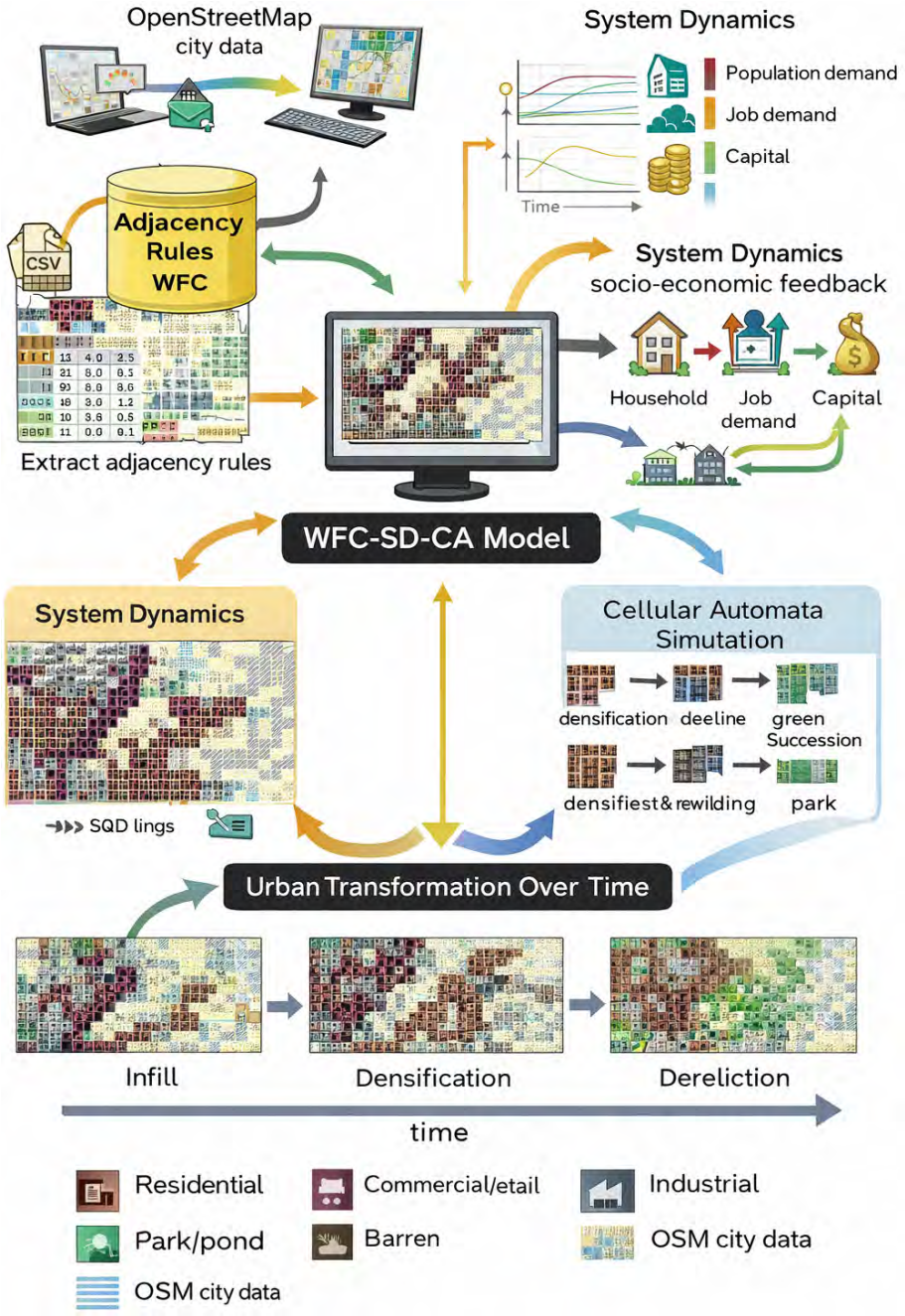

Fig. 1: Workflow used in our approach (Source: ChatGPT 5.3 when presented with our complete source code and input data)

Table 1: Classification of OSM tiles into our model

OSM key	OSM value	Mapped urban tile type	Meaning in the model
landuse	industrial	industrial	Productive / manufacturing land
landuse	residential	residential_split	Residential land (later split into high/low density)
landuse	commercial	commercial_split	Commercial land (later split into retail vs office)
landuse	retail	commercial_retail	Retail, shopping, consumer services
landuse	mixed	mixed_use	Mixed residential-commercial fabric
landuse	construction	barren (0.8 weight)	Under construction, treated as degraded land
landuse	brownfield	barren	Abandoned or previously used land
landuse	greenfield	barren (0.8 weight)	Unbuilt but developable land
landuse	farmland	farmland	Agricultural land
landuse	meadow	farmland (0.8 weight)	Open agricultural or semi-natural land
natural	wood	forest	Forested ecological land
landuse	forest	forest	Forested ecological land
leisure	park	park	Managed green space
natural	water	water	Lakes, ponds, rivers
water	any	water	All water bodies
waterway	riverbank	water	River edges
power	plant	infrastructure	Energy infrastructure
power	substation	infrastructure	Energy distribution

Table 2: Stocks (state variables)

Stock	Meaning in the model	What it represents
DESIRED_HOUSEHOLDS	Households that want to live in the city	Population pressure; demand for housing
JOB_DEMAND	Jobs firms want to fill	Size of the urban economy
CAPITAL	Economic investment potential	Financial capacity for growth

Table 3: Derived state variables (but not defined as stocks)

Variable	Definition	Role
ACTUAL_HOUSEHOLDS	min(DESIRED_HOUSEHOLDS, HOUSING_CAPACITY)	Population actually accommo-dated
HOUSING_CAPACITY	Sum of all housing slots in patches	Built housing supply
JOB_CAPACITY	Sum of all job slots in patches	Built employment space

3.4 System Dynamics Layer: Households, Jobs and Capital

On top of the spatial grid, we define three interacting stocks (Table 2 and 3): desired households, job demand, and capital. Actual households are realised as the minimum of desired households and the current housing capacity of the grid. Job creation and loss are formulated as proportional flows of job demand, where creation is supported by capital and by scarcity of usable business space, while loss increases under low urban quality and dereliction (compare with Tables 4 and 5). Capital itself grows and decays proportionally: investment inflow depends on urban quality, while capital flight increases with global vacancy and dereliction. This proportional formulation prevents "leakage to zero" and makes the dynamics scale with system size.

Table 4: Flows acting on stocks

Flow	Acts on	Mathematical driver	Urban meaning
NET_ MIGRATION	DESIRED_ HOUSEHOLDS	Depends on housing availability, job shortage and urban quality	People moving in or out
JOB_ CREATION	JOB_DEMAND	Increases when capital is high and business space is scarce	Firms expanding
JOB_LOSS	JOB_DEMAND	Increases with dereliction and low urban quality	Firms shrinking or leaving
INVESTMENT_IN FLOW	CAPITAL	Proportional to urban quality	Attractiveness to investors
CAPITAL_ FLIGHT	CAPITAL	Proportional to vacancy and dereliction	Disinvestment and decline

Table 5: Key feedback variables

Variable	Derived from	Meaning
BUSINESS_SPACE_AVAILABLE	Job capacity excluding derelict vs job demand	Indicates surplus or shortage of usable office/industrial space
VACANCY_LEVEL_GLOBALLY	Unused housing + jobs	How hollow the city is
DERELICTION	Mean derelict level of built patches	Structural decay
URBAN_QUALITY	Green per household, vacancy, dereliction	

3.5 Spatialisation of Demand: Fill-First Packing

Instead of distributing households and jobs proportionally across all available patches, the model uses a fill-first packing strategy. Residential patches are filled sequentially until actual households are assigned; employment patches are filled in the same way until job demand is met or job capacity is reached. This produces spatially concentrated vacancy: fully occupied neighbourhoods can coexist with fully empty ones, enabling realistic clusters of decline rather than thin vacancy everywhere.

3.6 Vacancy, Dereliction and Conversion to Barren Land

For each patch we compute housing and job vacancy fractions from used and available slots, and aggregate them into a capacity-weighted vacancy level. When vacancy exceeds a threshold, vacancy duration accumulates; otherwise it decays slowly back to zero. Dereliction is derived from vacancy duration, capped between zero and one. Once a patch reaches full dereliction and remains so for a specified period, it is converted to barren land and its capacities are reset according to the barren defaults. This provides a simple but effective mechanism for irreversible loss of built fabric under prolonged vacancy.

3.7 Urban Quality and Migration

Urban quality combines three components derived from the current spatial state: green availability per household, global vacancy, and mean dereliction across built patches. A preference parameter can scale the contribution of green. Net migration is implemented as a bounded rate that increases with urban quality and housing slack, and decreases with job shortage. As a result, macro-level household demand responds to both socio-economic opportunity and the emergent spatial condition of the city.

3.8 Built Evolution and WFC infill

Development pressure is computed from shortages in housing and jobs relative to capacity. Under sustained housing shortage, low-density residential patches may densify into high-density residential patches. In addition, empty, barren, park or forest patches adjacent to built fabric can become candidates for development. For each candidate patch, the WFC infill operator samples a new land-use type from the learned directional distributions. Each neighbour is treated as the “centre” of a rule, the direction is inverted relative to the candidate, and the candidate’s probability vector is obtained by multiplying these neighbour distributions. Sampling is then performed from the resulting weights. If the sampled type is “other”, the model skips infill for that patch in that tick rather than forcing a fallback land-use.

3.9 Nature Dynamics: Succession and Planned Greening

Nature enters as both spontaneous and planned transformation. Under decline pressure, empty or barren patches near existing green sources (forest, park or water within a radius) may convert to forest, capturing succession and rewilding. In parallel, planned greening can convert empty or barren patches near built areas into parks, modulated by green preference and suppressed under strong development pressure. Both processes act on the same grid representation and directly compete with development-driven infill.

3.10 Tick Ordering and Frozen Capacities

Because land-use transitions directly modify housing and job capacities, the simulation applies a strictly defined update sequence within each tick. The first step distributes households and jobs across the existing spatial configuration and updates vacancy levels and dereliction status accordingly. At this stage, all capacities still reflect the land-use structure inherited from the previous tick.

Next, spatial transformation processes are executed. These include densification of low-density residential areas under housing pressure, WFC-based infill of eligible candidate patches, and ecological transitions such as succession or planned greening. Each of these operations

may change land-use types and thereby alter local housing and job capacities. Importantly, the WFC operator acts on the current neighbourhood configuration without simultaneously triggering macro-level stock adjustments.

Only after all spatial transformations are finalised is the system-dynamics layer updated, recalculating capital, desired households and job demand. This separation is essential for the coupling of WFC and system dynamics: the generative spatial processes operate on a stable demand context, while the aggregate stocks respond to a temporally consistent and fully updated capacity structure. In other words, adjacency-driven land-use change and socio-economic feedback are coordinated sequentially rather than simultaneously. This prevents circular intra-step feedback and avoids sign reversals or artefacts that could arise if capacity changes and stock adjustments were evaluated within the same computational moment.

4 Case Study Hirschstetten/Breitenlee in Vienna/Austria

As a case study, we have applied our approach to the Hirschstetten and Breitenlee area in Vienna. The study area is framed by the Breitenlee nature conservation area in the north, a large mosaic of re-wilded former railway land with dry grasslands, woodland and habitat

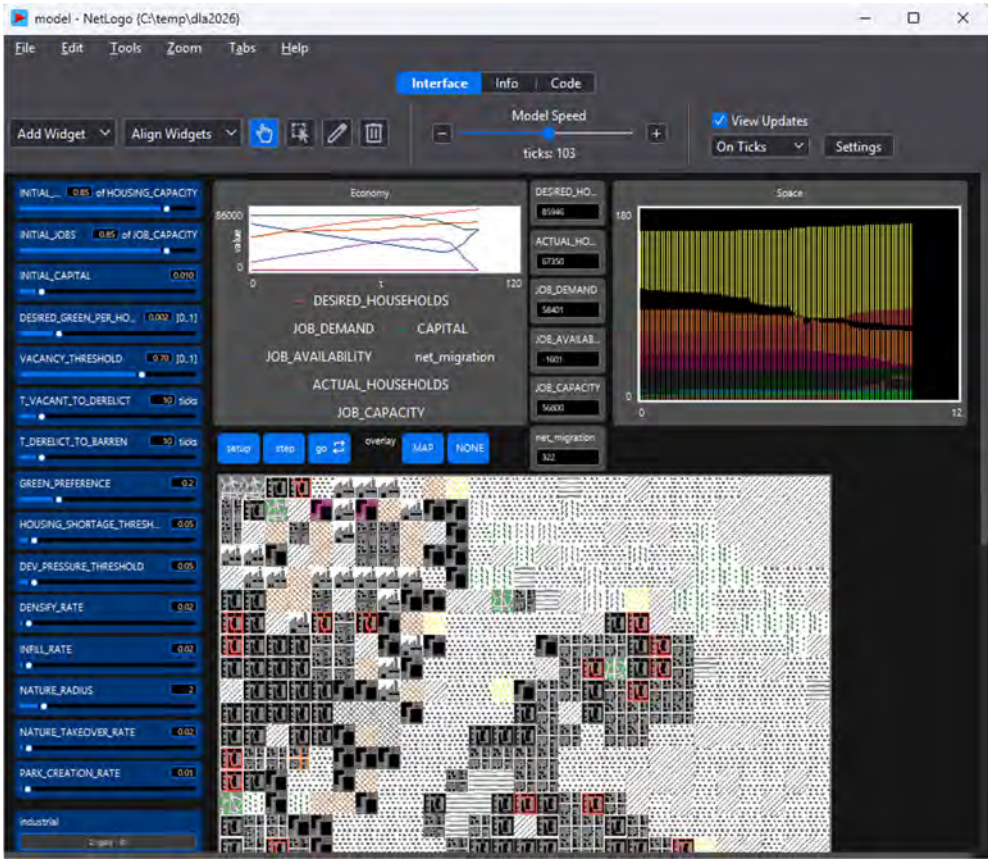

Fig. 2: Result of the simulation of the Hirschstetten/Breitenlee (own work, screenshot)

ponds; by the Breitenlee / Hirschstetten bathing pond and associated recreational green spaces in the centre; by the A23/S2 motorway corridor and associated arterial infrastructure to the east, which forms a hard infrastructural edge; and by the Danube corridor and its floodplain landscapes to the south, whose water bodies and riparian green belts structure the wider ecological and recreational context. Within these bounds, medium-density residential neighbourhoods, remnants of industrial and railway infrastructure, local commercial strips, and parks and gardens interlock to produce a highly heterogeneous urban-ecological interface, making the area a particularly rich testbed for studying transitions between built fabric, vacancy, infrastructure and emergent green systems.

Running our simulation for a time span of 100 years suggests a densification for residential areas (family houses to to multi-storey apartment blocks and mixed-use neighbourhoods), accompanied by the gradual infill of vacant and brownfield plots along infrastructural corridors, while ecologically valuable zones consolidate into continuous green corridors around the Breitenlee conservation area and the central pond, stabilising urban quality even under sustained population and employment growth. New green areas appear in two versions: as planned green (park) surrounded by densified resizential zones (see green tile surrounded by red tiles in the middle of Figure 2), and as unplanned nature spill into unoccupied/barren/derelict zones (see green patches in the northeast of the map in Figure 2).

5 Discussion

The proposed framework combines data-driven adjacency learning, spatial cellular logic and system-dynamics feedback within a single model of urban transformation. Its primary strength lies in this coupling: infill and densification are not applied globally or arbitrarily, but emerge from socio-economic pressure, vacancy and decline. The fill-first allocation of households and jobs produces spatially concentrated vacancy, enabling coherent patterns of dereliction and re-naturalisation rather than diffuse underuse. In this respect, the model captures both growth-driven development and decline-driven ecological succession within a unified spatial structure.

At the same time, several limitations must be acknowledged:

- Adjacency rules for the WFC component were calibrated using the same area that serves as the case study (Hirschstetten/Breitenlee). While this preserves local morphological character, it limits generalisability. Rules learned from a small area may reflect local particularities rather than city-wide structural tendencies. A broader calibration using the entire city – or multiple urban contexts – would increase robustness, but potentially reduce neighbourhood specificity. This trade-off between local fidelity and statistical representativeness remains an open methodological question.
- The long-term behaviour of the system reveals structural instability. In extended simulations (≈200 years), cumulative decline, job loss and capital flight can lead to systemic collapse. The model therefore does not support reliable projections over very long time horizons. A more realistic prediction window lies within medium-term scenarios (e.g. up to 100 years), where feedback between development, vacancy and green succession remains dynamically plausible. This limitation reflects both the simplified macro-economic structure of the SD layer and the absence of adaptive policy intervention within the model.

Further limitations concern abstraction level. The ecological component captures morphological succession but not hydrological processes, soil quality or biodiversity dynamics. Likewise, economic behaviour is aggregated into three stocks and does not differentiate sectors or institutional actors. Model outcomes therefore depend on parameter choices such as vacancy thresholds, densification rates and green preference. These parameters encode assumptions about tipping points and recovery speed that should be explored systematically in future work.

Despite these constraints, the framework demonstrates how generative algorithms and socio-economic feedback can be integrated to simulate bidirectional transitions between built and natural systems. Rather than predicting specific futures, the model is best understood as an exploratory tool for structured scenario testing under varying development, decline and greening conditions.

6 Conclusion and Outlook

This paper has presented a computational framework for modelling urban transformation as a coupled process between built and natural systems. By integrating data-driven Wave Function Collapse (WFC), system dynamics and spatial cellular logic within a single time-stepped model, the approach enables simulation of densification, decline, vacancy, dereliction and ecological succession within one coherent structure.

The principal contribution does not lie in proposing a new generative algorithm, but in embedding empirically learned adjacency rules within a demand-driven transformation model. WFC is shifted from a static pattern generator to a dynamic operator whose outputs are conditioned by socio-economic pressure, capital flows and spatial vacancy. This coupling allows the exploration of bidirectional trajectories: not only growth and infill, but also structural decline and re-naturalisation.

The Hirschstetten/Breitenlee case study demonstrates how this integration produces emergent spatial patterns that reflect both morphological coherence and macro-economic feedback. Concentrated vacancy, densification corridors and green succession arise from internal model dynamics rather than pre-scripted scenarios. At the same time, long-term collapse behaviour highlights the importance of bounded prediction horizons and the need for more differentiated economic and policy mechanisms in future extensions.

The framework is therefore best understood as an exploratory scenario engine rather than a forecasting tool. It makes explicit the interactions between adjacency structure, socio-economic demand and ecological processes, providing a platform for structured “what-if” experimentation in planning and design contexts. Future work should expand rule learning beyond local calibration areas, refine economic differentiation, and incorporate richer ecological processes to increase robustness across spatial and temporal scales.

By operationalising the interaction between morphology, economy and ecology in a single computational model, the work contributes to bridging generative urban design and dynamic urban simulation – moving from static land-use allocation toward the modelling of urban transformation as an evolving, feedback-driven system.

However, the more complex the task at hand the less likely solutions can be found in a compressed two-dimensional manner. Next research steps need to focus on how to represent the

co-evolution of urban and ecological systems in three spatial dimensions plus time dimension, while addressing multiple spatial, temporal, and functional scales. Furthermore, it will be useful to explore how the reported computational methods can be integrated into advanced data-driven workflows that utilize state-of-the-art spatio-temporal data-rich digital twins of cities, and AI-based ontology-aided rule-based processes towards comprehensive scenarios for equitable and ecologically valid urban futures.

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Digital Transformation at Half Speed: Fit for BIM or Fit for Yesterday? The Gap between Practical BIM Requirements and Curricula in Landscape Architecture Education

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Abstract: The ongoing digitalisation of planning and construction is bringing about lasting changes to work processes, role models, and skill requirements. With the introduction of the step-by-step plan for digital planning and construction, the Building Information Modeling (BIM) method is becoming increasingly important, including in landscape architecture, where professional practice demands "greater focus on digitalization." The aim of this study was to analyse the extent to which the training of future landscape architects at German universities already prepares them for the requirements of digitised planning practice.

Based on relevant specialist literature, a keyword catalogue was developed that systematically maps digital and BIM-specific skills. The module handbooks of selected degree programs in the context of landscape architecture were quantitatively evaluated using a Python-based text analysis method.

The results show clear differences between universities and areas of competence. While digital basics (e. g., CAD, GIS, 3D modeling) are taught across the board, BIM-specific terms are found in only a few references.

Keywords: Higher education, future skills, media skills, BIM

1 Introduction and Problem Definition

Digitalisation is inducing a systemic paradigm shift in planning, construction and management processes. Driven by the implementation of the "Digital Planning and Construction" roadmap (BMDV 2015), Building Information Modeling (BIM) is establishing itself as the mandatory standard for life cycle-oriented project management. While building construction and civil engineering have largely completed the transition from drawing-oriented to object-based modelling, the sub-disciplines of landscape architecture are still in an early phase of adaptation (KLUTH 2025).

This research evaluates the maturity of academic teaching in landscape architecture with regard to the requirements of digitised planning practice. The focus is on analysing the curricular anchoring of digital skills, specific BIM methodologies and the understanding of the continuous information chain. The relevance of this topic stems from the increasing penetration of digital methods into everyday professional life. Planning offices and contractors are faced with the challenge of making existing work processes compatible with BIM methodology. At the same time, young professionals need a skills profile that combines technological, methodological and communicative abilities in order to work in a model-based and interdisciplinary manner. Universities play a key role in this: they shape the professional identity of the next generation of landscape architects and thus have a decisive influence on the digital

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resilience and future viability of the entire profession. Ultimately, the profession also expects graduates to have the appropriate qualifications. In unpublished interviews conducted as part of the development of the degree programme, there was a clear demand for "more focus on digitalisation"; 20% of all mentions regarding the requirements of professional practice were in the block with the highest number of mentions, "digital tools and skills" (HOCHSCHULE GEISENHEIM 2024).

2 Theoretical Framework and Social Context

2.1 Conceptual Reference

The study is based on two conceptual reference points: firstly, the Future Skills Framework of the Stifterverband (SUESSENBACH et al. 2021), which defines 21 key skills for an increasingly digitalised, networked and transformation-driven world of work and secondly the European Digital Competence Framework for Citizens (DigComp), which operationalises digital skills in five dimensions from information and data literacy to problem-solving skills and creativity (VUORIKARI et al. 2022). Both models emphasise that digital competence goes far beyond the use of software. It encompasses systemic thinking, critical reflection, ethical action and the ability to develop oneself in a self-directed manner in dynamic technological contexts. These dimensions form the basis for defining digital education in landscape architecture not as pure technical training, but as cultural and methodological change.

Furthermore, the analysis refers to the requirements of the professional field itself. Studies such as that by Roland Berger (ROLAND BERGER GMBH 2020) on the digitalisation of the European construction industry show that the lack of digital skills among skilled workers has become a major bottleneck for innovation and productivity. While companies are increasingly looking for experts with model-based skills, universities are failing to systematically anchor such skills in their curricula. This imbalance forms the starting point for the present empirical study.

2.2 BIM in the German Context

BIM defines a collaborative working methodology based on the generation, management and use of digital building models throughout the entire life cycle. The aim is to achieve a continuous flow of information from planning and execution to operation and disassembly (EASTMAN et al. 2018). In Germany, the Digital Planning and Construction Roadmap (BUNDESMINISTERIUM FÜR VERKEHR UND DIGITALE INFRASTRUKTUR 2015) provides for the gradual introduction of the BIM methodology for all publicly funded construction projects.

At the same time, concepts such as the property information model (PIM) are gaining in importance. They extend the focus of the building model to include long-term operation, maintenance and the development of open spaces. In view of ecological resilience and adaptive planning, the convergence of BIM and AIM enables evidence-based decision-making processes, automated maintenance strategies and participatory procedures. Nevertheless, in practice, there has been a delay in curricular adaptation. The reasons for this lie in the complexity of the method, the heterogeneity of the software landscape and the disciplinary boundaries between civil engineering, landscape architecture and geoinformatics (DAMEK et al 2022).

3 Methodological Approach

The aim of the study was to determine the extent to which the content and skills specified in the curricula of landscape architecture programs at German universities prepare graduates for the requirements of digitalized planning practice. A two-stage mixed-methods design was chosen for this purpose.

3.1 Mixed-Methods Design

The study was based on the following method:

1) Quantitative document analysis of the curricula of bachelor's degree programmes in landscape architecture at German universities selected on the basis of the current publication by the BDLA (HAAS 2025); the analysis focuses on bachelor's degree programmes. The curricula were analysed automatically using a Python script.
2) Qualitative guided interviews with lecturers and programme coordinators to contextualise and validate the quantitative findings.

Based on relevant reference frameworks (including Future Skills Framework, DigComp, and profession- and BIM-related publications), five competency clusters ("categories") were formed as illustrated in Table 1. The identified keywords were assigned to these categories.

Table 1: Overview of categories with explanations, keyword examples

Category	Explanation	Keyword example
Basic digital skills	Fundamentals of digital work: digital literacy, data literacy, communication	Digital literacy
BIM-specific skills	Model-based methods, standards, coordination and information management	Building Information Modeling
Method & process skills	Agile, collaborative, interdisciplinary work; project and quality management	Project management
Technological skills	VR/AR, parametric design/scripting, AI/ML, robotics, sensor technology, IoT	3D modelling
Transformation skills	Sustainability, innovation and change competence, LCA, material passports	Life cycle analysis

For the use of the Python script, literature-based keywords were identified that represent relevant digital and BIM-related skills (BETZ et al. 2022, FEDERAL CHAMBER OF ARCHITECTS 2025, FEDERAL ASSOCIATION OF GARDEN, LANDSCAPE AND SPORTS FIELD CONSTRUCTION 2024, SUESSENBACH et al. 2021). Synonyms/English variants were added to increase the hit probability. The module handbooks were then analysed and visualised to highlight differences between universities and areas of expertise. The keyword search was implemented using a special Python script, which was developed with the help of ChatGPT (OPENAI 2025).

In addition, interviews were conducted to identify institutional frameworks, teaching strategies and perceived barriers to the integration of digital methods. This qualitative level allows quantitative patterns to be interpreted and examples of good practice to be identified.

3.2 Data Basis and Sample

This article focuses on the findings from bachelor's degree programmes; the results from master's degree programmes are not taken into account. This is primarily because a bachelor's degree represents vocational training. Secondly, bachelor's degree programmes are more structurally homogeneous. In contrast to master's programmes, which are characterised by a high degree of freedom of choice and individual specialisations, the high proportion of compulsory modules in bachelor's programmes allows for the identification of a consistent core competence profile. This curricular standardisation allows for a more precise derivation of the basic competences that are equally binding for all graduates at a given location.

3.3 Limitations and Validity

The study comprises a sample of twelve bachelor's degree programmes in landscape architecture at German universities. The selection process was conducted through a methodical survey of the available courses (as of Early 2025). The analysis is based on module handbooks as formal documents and does not necessarily reflect actual teaching practice (e. g. software used, project depth, topicality of content). The keyword search is sensitive to terminology, and despite synonyms, under-recognition is possible. Conversely, false positives may occur; these have been reduced through manual checking. Two metrics are distinguished for interpretation: (1) term frequency (number of relevant hits) as an indicator of curricular visibility and (2) module coverage (number of different modules per category) as an indicator of curricular anchoring. To avoid distortions due to multiple mentions within a teaching unit, module coverage was determined using unique module IDs. The module handbooks were evaluated automatically using a Python script (keyword search in the full text of the PDFs). The results included references with page references and a hit matrix for each degree programme. This was followed by a manual plausibility check of each reference (decision: relevant vs. false positive).

4 Results of the Quantitative Evaluation

The quantitative analysis identified a total of 430 descriptors. With a share of 51% (221 mentions), technological skills account for the absolute majority. Basic digital skills (29%, 126 mentions) and BIM-specific skills (17%, 75 mentions) have significantly lower curricular visibility. Methodological, process and transformation skills have only a marginal presence in the module handbooks examined (see Figure 1).

A corresponding distribution is evident in the module coverage (number of different modules) as shown in Figure 2: 160 modules contain at least one relevant reference; technological skills dominate with 86 modules (54%), while BIM-specific skills are only explicitly anchored in 34% of the few modules.

The concentration of BIM-specific references in a few curricula is striking. In the present sample, three degree programmes do not have any explicit BIM-specific hits; the remaining hits are heavily distributed across individual locations. This suggests not so much a lack of basic digital skills, but rather an insufficient methodological and organisational embedding of BIM (e. g. standards, CDE, roles/processes) in teaching.

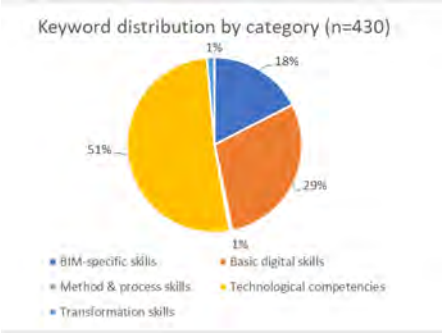

Fig 1: Distribution of the total number of keywords across the five categories (n=430)

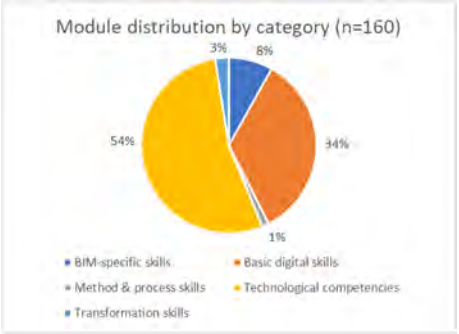

Fig. 2: Distribution of the total number of modules across the five categories (n=160)

The distinction between the distribution of hits in the area of compulsory modules and other modules (compulsory electives, electives) also makes it clear that, apart from basic digital skills (68 hits in the compulsory area vs. 58 hits in the compulsory elective area), BIM-specific and technological skills are (still) more strongly located outside the compulsory canon in the curricula.

Both in the compulsory area and in the compulsory elective/elective area, technology-oriented skills (e. g. CAD/GIS/visualisation) dominate, while methodological and process skills are almost invisible (only 1 reference and 1 module respectively). However, these skills are central to BIM, as BIM should not be understood primarily as a software issue, but rather as a method of information and collaboration (including roles/responsibilities, data and model coordination, standards, CDE working methods).

The results suggest that teaching does impart instrumental skills, but neglects the methodological prerequisites for organisational BIM implementation in professional practice.

At the keyword level, the frequencies (see Figures 3 and 4) support the category analysis: CAD/GIS and visualisation terms dominate in the compulsory area, while BIM-typical concepts are only found to a greater extent in the elective area. This suggests that digital planning is often operationalised in teaching as a tool competence (representation, geodata, CAD), while core BIM topics (model-based data exchange, standard formats, information-based coordination) are treated as optional rather than an integral part of basic training. The pure number of hits is put into perspective by the module coverage: although there are significantly more BIM-related hits in the elective area, these are spread across only a few modules (7). This proves that although BIM enjoys increased visibility in the elective area, it remains structurally fragmented.

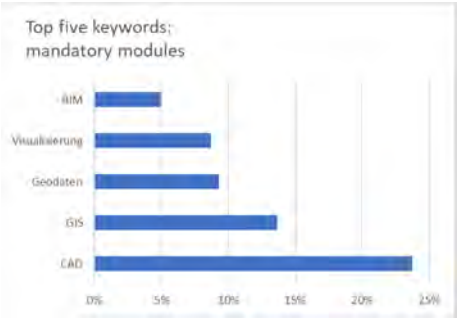

Fig. 3: Top 5 keyword hits and percentage share of total hits mandatory modules

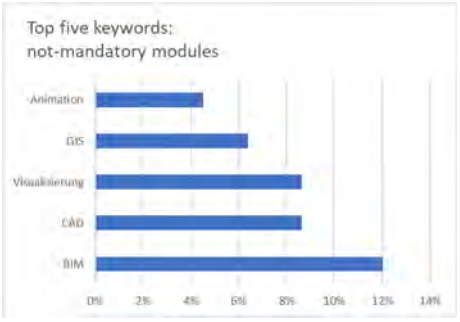

Fig. 4: Top 5 keyword hits and percentage share of total hits, not-mandatory (compulsory elective/elective) modules

The results suggest “BIM islands” (individual in-depth modules) rather than coherent, cumulative competence development over the course of the programme. There are almost no references to the operation and demolition phases of the life cycle. This is an indicator of the lack of connection between design, implementation and management.

Overall, the data attests to a “half-hearted digital transformation” at universities: development is fragmented and lacks a systemic institutional overall strategy.

The results allow several conclusions to be drawn

1) A digital basis is in place, but there is a lack of strategic depth.

While basic technological skills are taught, there is a lack of comprehensive process understanding. Students learn how to use digital tools, but not how to integrate them into a collaborative information model.

2) In modularised curricula, content is sometimes highly fragmented.

Digital topics often appear as elective modules or advanced courses, rather than as a continuous element of the curriculum. This additivity prevents the development of a consistent competence profile.

3) There is a lack of orientation towards the life cycle perspective.

Teaching content focuses heavily on the design and planning phases. Aspects of the operation, maintenance and reuse of open spaces (central fields of application for AIM) remain largely unaddressed.

4) Last but not least, universities struggle with didactic and structural barriers.

Interviews and secondary sources show that the integration of BIM into university teaching in Germany is hampered by several didactic and structural obstacles. A key deficit results from the often limited methodological and technical expertise of teaching staff, which makes it difficult to adequately teach digital planning methods. The Federal Chamber of Architects states that so far “only a few professors [...] have explicitly included digital planning methods in their teaching” and that “systematic training in digital planning” is largely lacking (BAK,

2021). In addition, there are institutional barriers: due to long-term personnel and financial structures, universities can "...only respond to trends in practice to a limited extent." The introduction of digital teaching content requires "...structural, financial and personnel resources...", particularly with regard to software licences, computing power and common data environments (CDE), which are not yet available in many places (BUNDESARCHITEKTENKAMMER 2021).

5 Recommendations for Action

Three key areas of action are proposed to promote future-proof education:

1) Curricular integration: Development of a modular competence framework "Digital Planning and BIM in Landscape Architecture" based on future skills approaches and the DigComp model.

2) Didactic innovation: Introduction of interdisciplinary integrated design studios in which students work on model-based planning projects across disciplines.

3) Structural cooperation: Establishment of inter-university alliances for the development of teaching materials, open-source databases and joint real-world laboratories for digital open space planning.

The findings show that "BIM readiness" is not primarily achieved through additional software instruction, but through the curricular anchoring of a binding core set of competencies. This includes at least: principles of information modelling, data and quality management (e. g. attribute logic, validation rules), collaboration and roles/processes throughout the project life cycle (CDE working methods), as well as standard and exchange skills (openBIM/IFC as a principle). Elective modules can build on this and offer more in-depth knowledge (IFC workflows, interdisciplinary project studios, model review/VR scenarios). However, they must not replace the infrastructural foundation of basic training.

The master's module "Interdisciplinary Application of Building Information Modeling" can serve as a practical reference format: landscape architecture students work together with students from other disciplines across universities on a project that is exclusively model-based in a Common Data Environment (CDE).

Fig. 5:
Joint kick-off workshop: Students explore models in virtual space

After a joint kick-off workshop (see Figure 5), the collaboration takes place online in a virtual project environment; interdisciplinary teams develop and coordinate planning statuses on the shared model, discuss decisions virtually and present the results in a digital tour. An accompanying BIM manual documents the BIM phases, including issues, role definitions and coordination challenges, thus reflecting key requirements of future professional life.

Although this example comes from a master's context, it serves as a blueprint for comparable formats that can be easily integrated into bachelor's programmes, especially at universities where related disciplines (e. g. architecture, urban planning, infrastructure/civil engineering) are available for interdisciplinary teaching collaborations.

6 Conclusion and Outlook

This study shows that bachelor's degree programmes in landscape architecture in Germany are on the path to digital transformation, but this process is currently proceeding at a significantly reduced pace, at half speed, so to speak. While initial adaptation processes are evident in teaching, the necessary methodological and cultural shift has so far been slow to materialise. The results underscore the urgent need to no longer interpret BIM as a purely technological innovation, but to operationalise it as a new paradigm for cooperative, data-based and sustainable planning. Only in this way can we respond to the statements of professional practice in a future-proof manner: “BIM is becoming increasingly important, but we don't have anyone who can really do it” (HOCHSCHULE GEISENHEIM 2024).

Furthermore, there are plans to scale up the methodology and deepen qualitative findings. The overarching goal is to design a “BIM Competence Framework for Landscape Architecture” that will serve as a standardised reference framework for curriculum development and quality assurance in digital teaching at universities. Extending the comparison to landscape architecture study programs outside Germany could enable positioning in an international comparison. This would allow best practice examples to be identified and implemented in German university teaching. The study thus makes a significant contribution to the evidence-based discussion about the future of academic education in landscape architecture, a discipline that, to stay with the metaphor, has already started the engine but has not yet shifted into gear.

Acknowledgements

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Mapping the Scope of Computational Design

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Abstract: This study investigates the scope of computational design and environmental parameter integration within landscape architecture and planning. Employing a structured scoping review and scientometric co-occurrence analysis of literature published between 2010 and 2025, the research explores the relationships between spatial scales, environmental metrics, and digital workflows. The results indicate a significant bias toward the built environment, where BIM/BEM and parametric tools are predominantly used for energy and comfort optimization at the building and urban block levels. Conversely, ecological and hydrological systems are largely relegated to analytical roles within GIS frameworks rather than serving as active drivers for design optimization. The findings highlight a critical gap in computational tools for green-blue infrastructure, which currently hinders the effective integration of landscape parameters into BIM/BEM simulation and further application in Life Cycle Assessments (LCA).

Keywords: Computational design, landscape architecture, environmental parameters, design optimization, scientometric analysis, parametric design

1 Introduction

The paper considers design as a process, which involves analysis, defining of a problem and problem solution. With the emergence of design thinking in the first half of 20th century, the purpose of a design is the integration of knowledge into the problem solution and the providing of a scientific base for the design (BUCHANAN, 1992). The landscape as such precedes the landscape architect, while, in comparison, a piece of architecture under no circumstances precedes the architect (GIROT, 1999). The massive digitization of all aspects of the environment (FRICKER & MUNKEL 2015) and the design process has provided designers with powerful tools for the optimization of their designs.

Sensu lato, the optimization involves evaluating a design according to a set of predefined performance criteria and selecting the best-performing alternatives from a range of possible configurations. In architectural design the optimization refers to circulation pathways, floor plan layouts, or energy performance (WORTMANN & NANNICINI 2017). In landscape architecture, similar optimization workflows are used to evaluate hydrological performance, solar exposure, or habitat connectivity – linking design intent with environmental processes (HARMON 2024, MROSLA et al. 2025).

The term data-driven design refers to using measured or simulated environmental data as an input that feeds the process of computational design. Speaking of simulation, we need to contextualize the topic and distinguish between simulation and optimization. Simulation refers to a process that evaluates performance of a particular design against criteria, whereas optimization aims at the best-performing design based on simulated results (WORTMANN & NANNICINI 2017). However, in most cases the process incorporates both methods (TYC et al. 2024).

Optimization is enabled due to the widespread presence of parametric design environments such as Grashopper (RUTTEN 2013) that generates a wide range of possible designs that can

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be evaluated against a selected set of criteria or generate and optimize architectural forms or site layouts.

The authors have a professional background in landscape architecture and planning, utilizing 3D modeling software and GIS in their practice. This article was developed to map specific environmental parameters that can be modeled and simulated within the context of landscape architectural practice and identify gaps that might be focused on in further research community. Identification of gaps might provide better integration of simulation of a digital tool into scenario-based planning or life cycle assessment. In this paper, we present a comprehensive review of the literature that integrates environmental parameters within the framework of data-driven and computational design. The study aims to identify the range of environmental parameters addressed, the types of data most frequently utilized, and, ultimately, the spatial and methodological scales at which the projects are conducted.

2 Method

This paper employs a structured scoping review with semantic classification (TRICCO et al. 2018) to investigate how environmental performance parameters are operationalized within computational design frameworks in landscape architecture, followed by an evaluation via scientometric co-word analysis. Co-word analysis is a content analysis technique that uses patterns of co-occurrence of pairs of items in a corpus of texts to identify the relationships between ideas within the subject areas presented in these texts (HE, 1999). Literature searches were conducted across Web of Science, Scopus and Google Scholar with a set of four queries (Tab. 1). Query sets combined parametric or data-driven design concepts with landscape-, GIS- or Grasshopper-oriented modeling contexts. The initial queries were aimed at selecting topic in the field of landscape architecture, urban design and landscape planning spanning from 2010 to 2025.

Table 1: List of initial queries used for Web of Science, Scopus and Google Scholar Database

Query	Focus	Structure (concept clusters)
Q1 – Broad / GIS	Landscape × Parametric × GIS	(“parametric design” OR “parametric modeling” OR “data-driven design” OR “design optimization” OR “computational design”) (“landscape architecture” OR “landscape planning” OR “urban design” OR “green infrastructure”) (“GIS” OR “QGIS” OR “ArcGIS”)
Q2 – Broad / Grasshopper	Landscape × Parametric × Grasshopper	(“parametric design” OR “parametric modeling” OR “data-driven design” OR “design optimization” OR “computational design”)
Q3 – Narrow / Grasshopper + Environmental metrics	Parametric × Grasshopper × Stormwater / UHI etc.	(“parametric design” OR “parametric modeling” OR “data-driven design” OR “design optimization”) (“Rhino" OR “Grasshopper”) (“stormwater” OR “runoff” OR “infiltration” OR “soil carbon” OR “soil disturbance” OR “biodiversity” OR “microclimate” OR “building energy” OR “urban heat island”)
Q4 – Narrow / GIS + Environmental metrics	Parametric × GIS × Stormwater / UHI etc.	(“parametric design” OR “parametric modeling” OR “data-driven design” OR “design optimization”) (“GIS” OR “QGIS” OR “ArcGIS”) (“stormwater” OR “runoff” OR “infiltration” OR “soil carbon” OR “soil disturbance” OR “biodiversity” OR “microclimate” OR “building energy” OR “urban heat island”)

The initial search performed via the Publish or Perish 8 software (HARZING 2022) yielded 2014 records, which were de-duplicated and filtered to exclude non-English and thematically irrelevant outputs. A dataset of 1000 publications was retained for manual semantic screening. Article titles and abstracts were screened and included only if they addressed design-oriented modeling in architecture and landscape architecture. This resulted in a curated subset of approximately 597 publications positioned at the intersection of landscape architecture, urban design, landscape planning that leverages computational methods, either design or analysis.

Table 2: Environmental parameters and affiliated keywords

Category	Cluster Group	Keywords
Scale	Buildings	building, architecture, architectural, indoor, interior, façade, facade, energy efficiency, HVAC, building envelope, retrofit, thermal comfort, BIM, indoor comfort, ventilation
	Urban	city, urban design, block, infrastructure, mobility, municipality, urban, urban planning, urban morphology, street, public space, square, zoning, neighborhood, neighborhood, park
	Urban / Landscape:	green space, parks, park, stormwater, urban vegetation, urban forest, urban green, green infrastructure, blue infrastructure, green space, open space, nature-based solution, NbS, sustainable drainage, SuDS, Sponge city, urban heat, urban heat island, heat island, UHI, open spaces, outdoor thermal comfort
	Landscape / Regional	watershed, catchment, region, ecosystem, biodiversity, hydrology, land use, gis, remote sensing, landscape planning, climate change, landscape, river basin, basin, floodplain, agriculture, grassland, ecosystem, biodiversity, soil, regional, territory
Environmental Parameters	Climate / Environment	climate, microclimate, temperature, heat, cooling, humidity, atmosphere
	Sun / Shading	sun, solar, daylight, insolation, sunlight, shading, shade, irradiance
	Energy / Comfort	energy, performance, thermal, comfort, efficiency
	Water / Hydrology	runoff, stormwater, infiltration, hydrology, flood, drainage, water
	Ecology / Landscape	biodiversity, vegetation, soil, green, ecological, ecosystem, habitat
	Connectivity / Other Spatial	connectivity, accessibility, integration, network, visibility, walkability
Data Type / Workflow	GIS	GIS, geospatial, ArcGIS, qGIS, spatial analysis, remote sensing, mapping
	Rhino / Grasshopper	Rhino, Grasshopper, parametric, computational design, generative
	CFD	CFD, fluid dynamics, airflow, wind, ventilation, aerodynamics
	BIM/BEM	BIM, building information modeling, energy model, simulation, Revit, thermal performance

The dataset of 597 publications was then subjected to semantic screening based on scale (building, urban, urban/landscape, regional landscape), the environmental parameters used, and the workflow and data types. Initially, individual groups were categorized based on specific keywords (Tab. 2); a category was assigned to a Cluster Group if the keyword appeared in the title or abstract. In cases where keywords from two different categories were identified within the same title or abstract, an entry was assigned to both Cluster Groups. Subsequently, the presence of the keywords "Design", "Generative Design", "Simulation Analysis" and "Optimization" was incorporated to determine their frequency within each Cluster Group. The frequency of keywords within individual Cluster Groups was then evaluated using the same methodology. Semantic classification was conducted using RStudio (Posit 2025).

3 Results

This research focused on mapping the computational design landscape by analyzing domain representation across different spatial scales, environmental parameters, and data-driven workflows. The study tested the premise that design and optimization tools are concentrated at the building and urban block levels, while GIS is utilized primarily for regional and city-wide analysis. In the second step, we evaluated the distribution of individual environmental factors, that can be modelled and optimized, such as microclimate, shade, runoff, etc., and compared them to their workflow GIS/BIM/RHINO. Lastly, we reviewed the occurrence of keywords *design*, *optimization*, *simulation*, *analysis*, and *generative design* within subjected workflows.

The findings are illustrated through chord diagrams that evaluate the co-occurrence between keywords and cluster groups, alongside Sankey diagrams that function similarly by establishing links between these variables. In the Sankey diagrams, cumulative results may exceed 100% in instances where a single keyword is attributed to multiple categories.

3.1 Computational Workflows and Their Affiliation with Spatial Scales and Environmental Parameters

First of all, it is necessary to mention several key facts ensuring proper interpretation of these results. While the analysis shows that the four spatial scales (building, urban, urban landscape, and landscape-regional) are equally represented, the environmental factors indicate that the dataset is biased toward built-environment design and optimization. Natural or nature-based processes are less frequently simulated or parametrized, as evidenced by the low occurrence of the Connectivity (5.4%), Ecology & Land (10.3%), and Water & Hydrology (13.4%) categories.

BIM/BEM shows the highest degree of spatial specialization, with 74.2% (N=89) of its applications focused on the building's scale. Similarly, Rhino/Grasshopper serves as a bridge between the architectural and neighborhood levels, with significant representation in both Buildings (N=206) and Urban (N=164) scales. These findings strongly support the hypothesis that parametric design and building-performance simulation tools are concentrated at the building and urban block levels. On the other hand, GIS is the dominant tool for large-scale analysis, appearing in 36.6% of all technology co-occurrences and showing its strongest presence at the Landscape Regional level. This confirms that while design-centric tools (Rhino/

BIM) handle the “micro” and “meso” scales, GIS is the “macro” engine for city-wide and regional territory mapping. These were the expected outcomes. Less expected was that BIM/BEM are currently the least utilized tools for the design and simulation of green blue infrastructures like parks, green spaces, and urban vegetation, which are led by GIS-based workflows instead.

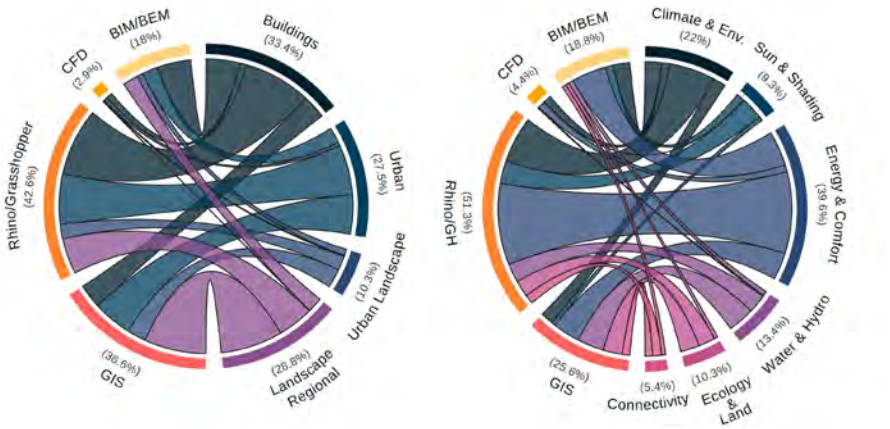

Fig. 1: Chord diagrams showing relationship of workflow and spatial scale (left) and environmental cluster groups

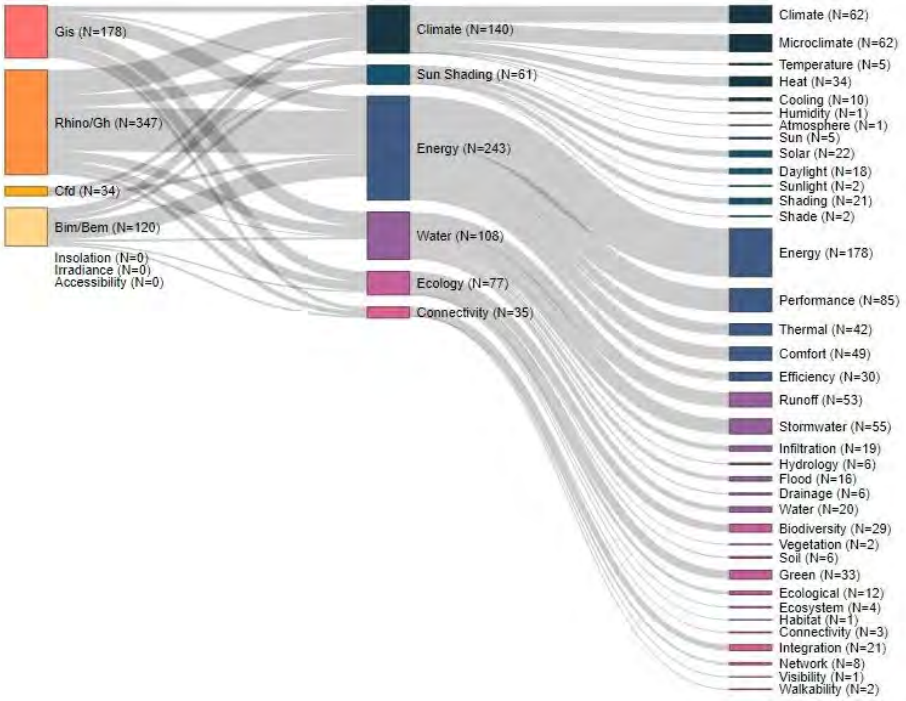

Fig. 2: Chord diagrams showing the relationship between workflow (left) and environmental cluster groups (middle) and keywords within the cluster groups (right)

Regarding environmental modeling, Rhino/Grasshopper serves as an all-containing hub, displaying the most diverse inputs by connecting all evaluated environmental parameter cluster groups. BIM/BEM and CFD workflows are more specialized, concentrating heavily on Climate, Energy/Comfort, and Sun/Shading, and least on Water, Ecology, and Connectivity. A parametric workflow where geometry is iteratively optimized based on light and thermal performance is an established territory. The GIS workflow is dominant in Hydrology and Ecology and, surprisingly, in Energy, while being less frequent in Climate. These findings justify the expectations of the authors and delineate two distinguished domains: BIM/BEM for Climate, Energy, Sun, and Shading at the building and urban block scale, and the GIS domain for modeling environmental flows – such as water, ecology, and connectivity – in large-scale and non-built-up environments.

3.2 Keywords: Design, Simulation, Optimization and Analysis

The results underscore a significant technological partitioning that depends on the environmental parameters being modeled. The design integration rate – defined as the frequency with which a parameter is explicitly coupled with design methodologies – demonstrates that Sun and Shading (51%) and Energy and Comfort (47%) are most closely tied to performance-driven design. This finding is corroborated by the technological profiles of Rhino/Grasshopper (84.1%) and CFD (85.3%), which exhibit the highest prevalence within the design category. In contrast, territorial processes such as Water (20%) and Ecology (33%) exhibit lower design integration and remain primarily analytical. This observation is reinforced by the functional orientation of GIS-based workflows, which prioritize Analysis (23.6%) over Simulation (12.9%), and BIM/BEM, where the focus shifts predominantly toward Simulation (70.8%). Collectively, these findings suggest that computational design practices remain concentrated on building-scale energy optimization and form-environment interactions, whereas ecological and hydrological systems are predominantly treated as analytical constraints rather than active design drivers (Fig. 3., Tab. 3).

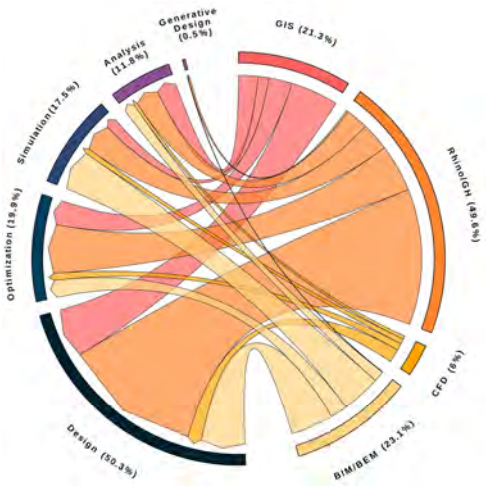

Fig. 3.:
Co-word occurrence of design related keywords with workflows presented as a chord diagram

Table 3: Co-word occurrence of design-related keywords and workflows indicates the total paper count for each keyword

Keyword	GIS (N=178)	Rhino/GH (N=347)	CFD (N=34)	BIM/BEM (N=120)
Design (N=489)	57.90%	84.10%	85.30%	76.70%
Optimization (N=242)	28.10%	29.70%	44.10%	30.00%
Simulation (N = 162)	12.90%	17.30%	32.40%	70.80%
Analysis (N = 168)	23.60%	14.10%	20.60%	19.20%
Generative Design (N=5)	0.00%	1.20%	0.00%	0.80%

The analysis of frequency shows dominant integration of Energy & Comfort into the Sankey diagram revealing a highly centralized computational landscape where environmental design is fundamentally driven by building performance metrics. The massive flow from Design (N=489) and Optimization (N=242) toward the Energy & Comfort cluster – specifically targeting keywords like Energy (N=250), Performance (N=218), and Efficiency (N=144) – demonstrates that algorithmic tools are primarily utilized as engineering engines for energy-efficient synthesis.

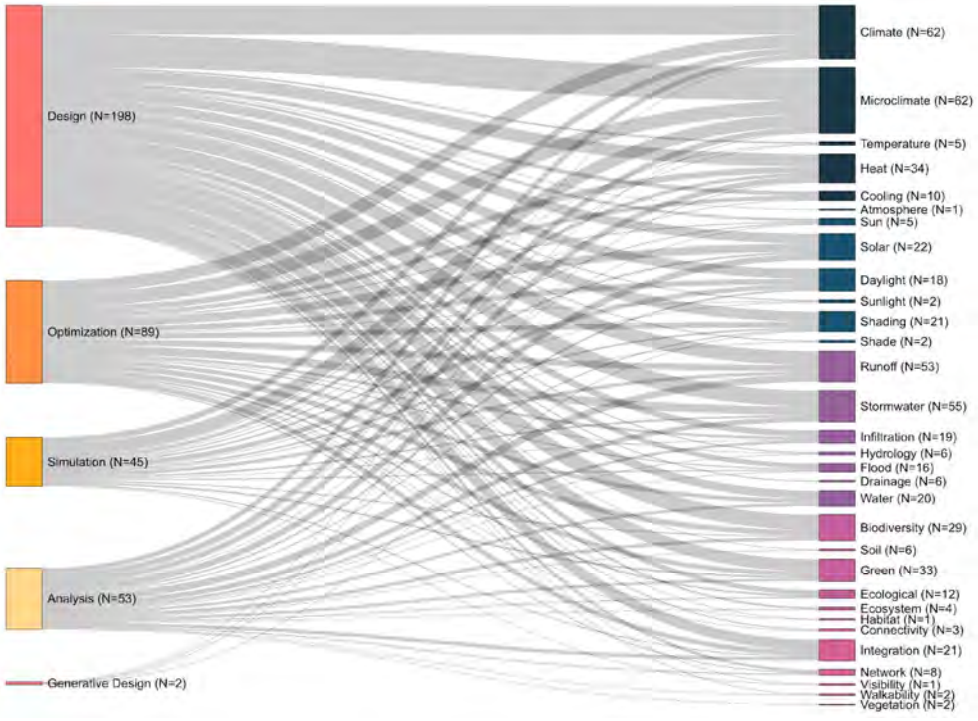

Fig. 4: Sankey diagram showing the relationship of workflow (left) and its abundance within individual keywords (right). The cluster groups were disaggregated into individual keywords.

When the dominant Energy & Comfort cluster is removed (Fig. 4), a more nuanced visualization of environmental parameters is revealed. The design integration rate – indicating how often "Design" is explicitly coupled with environmental parameters – reveals that Sun and Shading (73.8%) and Energy and Comfort (76.5%) are the most deeply integrated into performance-driven workflows. In contrast, Water and Hydrology and Ecology show significantly lower design coupling, at 47.2% and 58.4% respectively, appearing more frequently in purely analytical contexts. Notably, specific territorial parameters like Stormwater exhibit a remarkably low explicit analytical labeling, with only 7 out of 55 papers (12.7%) using the term "analysis".

4 Discussion

During the research, several factors emerged that may have influenced the findings and their interpretation. The authors consider it essential to address these points to provide the reader with the necessary context for interpreting the results.

Although the keywords were selected to capture a broad spectrum of both analytical and design-oriented articles, the resulting dataset exhibits a noticeable skew toward building architecture and construction. This is evident from the significant volume of papers focusing on energy and comfort, as well as the relatively low representation of GIS in relation to environmental parameter modeling. This discrepancy may be attributed to terminological nuances, specifically the varying use of terms such as "modeling", "analysis", "assessment", and "evaluation". Furthermore, the broad definition of "design" – which is frequently applied in diverse contexts beyond creative disciplines like architecture and landscape architecture – impacts the results. Consequently, environmental parameters more closely associated with landscape architecture and green infrastructure appear less prominent. This is further compounded by the fact that landscape architecture remains a niche field, in quantitative analyses often overshadowed by more dominant disciplines.

Potential bias may also stem from the nature of the Scopus and Web of Science databases, which primarily prioritize scientific research; architectural fields are often under-indexed, and their publication frequency is significantly lower than that of purely scientific disciplines. To mitigate this, we incorporated data from Google Scholar, which indexes sources such as Cumincad and other architecture-focused publication outlets.

In the field of landscape architecture, the relevance of design optimization gains importance with regard to the Life Cycle Assessment (LCA) method that may evaluate design impact service throughout its entire life cycle (NUGENT et al. 2022). A valid premise suggests that building design can be optimized to improve its Life Cycle Assessment, however, a pertinent question arises: Can landscape architecture achieve a comparable impact on LCA assessment?

The dual role of design lies in distinguishing between the carbon footprint and the carbon handprint (WESTERHOLM 2024). While the former represents the environmental burden (emissions generated by the project itself), the Handprint is generated in a way that the design choices lead to avoided emissions or enhanced sequestration for the city or the adjacent building. A possibility to predict and evaluate carbon handprints of a design may improve the acceptance of nature-based solution not only sociologically, but also economically.

5 Conclusion

Optimization and design workflows are well-established, particularly within the architectural domain, facilitating the inclusion of building-scale parameters in Life Cycle Assessments (LCA). However, a significant gap in the literature remains regarding the optimization of external environmental parameters – such as connectivity, urban greenery, stormwater management, and surface runoff. Although workflows utilizing platforms such as Revit and Dynamo, Rhino.Inside.Revit, or Vectorworks, as well as Rhino-based plugins like Lands Design already exist, their application to these specific metrics is underrepresented. This suggests that computational tools for the vegetative components of landscape architecture are either insufficiently documented, inadequate, or perceived as niche. This deficit prevents a full integration of green infrastructure benefits into the LCA of both individual buildings and entire districts, identifying a critical trajectory for future research and development. Furthermore, the traditional dichotomy – where GIS is reserved for analysis and Rhino/CAD for design – was not confirmed by evaluating the presented dataset. Instead, new domains are emerging: BIM/BEM dominates the scale of buildings and urban blocks, while the GIS domain remains the primary vehicle for modeling environmental flows, such as water and ecology, within large-scale and non-built environments.

Supplementary Dataset

RAW anonymized csv dataset is available here:
https://figshare.com/s/3ca90f87d63911614b42

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Tracking the Digital Shift: Eight Years of Software Trends in Landscape Architecture Curricula in the United States

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Abstract: This study presents a longitudinal comparison of software instruction in accredited landscape architecture programs across the United States, drawing on survey data collected in 2016 and 2024 to document the integration of software in curricula, especially drafting, rendering, modeling, and publishing software. This provides insight into changes in digital literacy and curriculum design. Findings reveal an increase in the number of software programs taught, a rise in the instructional depth of established tools, and the emergence of artificial intelligence (AI) as a cross-curricular technology. Most notable is the ascendance of *Rhinoceros 3D* (Rhino) over *SketchUp* as the leading 3D modeling software taught in academic programs, a shift that signals potential downstream adoption in professional practice. We conclude that while some trends reflect professional demands, others indicate academia assuming a leadership role in pioneering new digital tools and workflows.

Keywords: Landscape architecture education, digital literacy, design software, curriculum development

1 Introduction

The practice of landscape architecture has long relied on evolving tools and techniques for representation and communication. For much of the twentieth century, this work was primarily analog, driven by pencils and pens, watercolors, and markers (CANTRELL & MICHAELS 2015). In recent decades, however, digital software has become central to every stage of the design process, transforming how design is developed, represented, and constructed. These shifts, often rapid, require educators to continually reevaluate which software to teach and how deeply to integrate it into curricula (TAI 2003, MEADOWS 2021). As a result, landscape architecture has increasingly come to depend on digital tools that support spatial analysis, creative development, and design communication.

Several technological milestones have shaped this evolution in both academia and practice. Ivan Sutherland's Sketchpad in the early 1960s introduced graphical interaction with computers (ERVIN 1999), while the release of AutoCAD in 1982 marked a turning point in computer-aided drafting and professional workflows (WALKER 1994). Geographic information systems (GIS) became widely adopted in the 1990s, followed by the emergence of accessible 3D modeling software such as SketchUp in the early 2000s. In parallel, visualization tools like Adobe Photoshop and rendering engines such as Lumion and V-Ray significantly advanced representational quality and efficiency (GEORGE et al. 2019). More recently, artificial intelligence (AI), virtual reality (VR), and drone-based data collection have created new intersections between design, technology, and pedagogy (FERNBERG & CHAMBERLAIN 2023, GEORGE & SUMMERLIN 2019).

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Despite these advances, the integration of digital technology into landscape architecture education has rarely been seamless. Early studies documenting the introduction of computers into academic programs reveal that adoption was shaped as much by constraint as by opportunity. PALMER (1994) identified significant disparities in access to hardware and computing resources across institutions, with many students relying on outdated systems that limited their ability to engage emerging software. Faculty concerns extended beyond access to include the substantial time required to develop technical proficiency and questions about whether this emphasis might detract from foundational design instruction. These critiques were not opposed to technology itself but reflected an effort to balance innovation with the preservation of core pedagogical values within studio education.

This tension between efficiency and creativity has persisted through waves of technological change. As digital tools became more powerful and widespread, scholars questioned whether increased reliance on software enhanced design thinking or encouraged formulaic approaches to problem-solving. TAI (2003) noted early concerns that efficiency gains could foster a "cut-and-paste" mentality, prioritizing speed and polish over exploration and iteration. Similar critiques later accompanied parametric modeling and advanced visualization tools, where expanded technical capacity was often paired with heightened expectations for productivity and output. These recurring debates underscore that technological adoption in landscape architecture is not merely a technical issue, but one that directly shapes design culture, values, and expectations.

What compounds these concerns is the ongoing challenge of alignment between education and professional practice. While educators are tasked with preparing students for employment, they must also ensure graduates develop adaptable skillsets capable of responding to rapid technological change. Multiple studies have identified persistent discrepancies between the software emphasized in academic programs and the tools most commonly used in practice. GIS, for example, has long been widely taught in universities, yet its adoption in professional offices has lagged behind (TAI 2003, MEADOWS 2021). Similar misalignments have been observed with certain 3D modeling and visualization platforms, complicating curricular decision-making as programs weigh immediate employability against broader conceptual understanding and long-term professional flexibility.

In recent years, the scope of digital integration has expanded beyond software alone to include complementary technologies that further reshape design workflows. VR has emerged as a powerful visualization tool, offering immersive experiences that enhance spatial comprehension and client communication, though adoption remains uneven due to cost, technical complexity, and limited integration with established workflows (GEORGE & SUMMERLIN 2019). Drone-based data collection has similarly gained traction, enabling more efficient site analysis and documentation while introducing new technical and regulatory considerations. AI represents the most recent and potentially transformative development, generating significant interest for its potential to support visualization, ideation, and analysis, even as its role within formal curricula and professional practice remains emergent (FERNBERG & CHAMBERLAIN 2023).

STEFFENS (2017) and MEADOWS (2021) traced the continued diversification of digital tools, noting that software adoption has become a defining component of the professional skillset for emerging designers. However, much of the existing literature captures technology use at a single moment in time, offering valuable but fragmented snapshots of digital integration.

The present study responds to this gap through a longitudinal comparison of software instruction in landscape architecture programs in North America, primarily within the United States. By examining changes over an eight-year period, this research provides a more consistent view of how digital tools are being taught, how instructional priorities have shifted, and how landscape architecture education continues to adapt within a rapidly evolving technological landscape.

2 Research Methods

This study compares results from two national surveys conducted in 2016 and 2024 that measured the software and emerging technologies taught in accredited landscape architecture programs across the United States (Figure 1). Both surveys targeted faculty members primarily responsible for digital instruction in Landscape Architectural Accreditation Board (LAAB) accredited or candidacy programs. The 2016 survey included responses from 27 of 69 programs (39%), while the 2024 survey included responses from 48 of 76 programs (63%). Findings from the 2016 and 2024 surveys have been reported previously (SUMMERLIN et al. 2017, SUMMERLIN & GEORGE 2024); the present study focuses on a longitudinal comparison of these datasets to examine changes in software instruction over time.

The surveys organized software into broad categories: drafting (subdivided into 2D drafting and geospatial software in the 2024 survey), 2D rendering, 3D modeling, 3D modeling plug-ins, and desktop publishing. An additional software category captured write-in responses. Questions were also included regarding instructional methods and hardware. The 2016 survey consisted of 57 questions, while the 2024 survey expanded to 79 questions, primarily due to the inclusion of mobile device software and emerging technologies such as virtual reality (VR) and artificial intelligence (AI), as well as the addition of newly released software.

Each survey employed a 0-4 Likert scale to measure the instructional depth for each software package:

0 – The software is not taught in the curriculum.
1 – Students are introduced to the software and its capabilities.
2 – Students are shown a few techniques for specific tasks.
3 – Students can integrate several techniques into a design workflow.
4 – Students are proficient in using the software for discipline-specific use.

To ensure comparability between the two studies, the Likert scale, core survey structure, and analysis methods were retained. Data were analyzed primarily using rank-ordering based on response means to indicate which software tools were most emphasized in curricula. A Mann-Whitney U test, a non-parametric test appropriate for Likert-scale data, was employed to assess differences between the 2016 and 2024 survey results, allowing comparison of distributions despite differences in respondents across years. The resulting p-value indicates the probability that observed differences occurred by chance. Consistent with standard practice, differences were considered statistically significant when $p < 0.05$, meaning there is less than a 5% probability that the observed change reflects random variation rather than a meaningful shift over time.

3 Results

Across all software categories, results indicate an overall increase in instructional depth between 2016 and 2024, though the magnitude and statistical significance of change varied by software type. Several core platforms remained dominant across both survey years, while notable shifts occurred within 3D modeling, rendering, and select drafting tools.

Within the 2D drafting and spatial category, AutoCAD remained the most deeply taught drafting software, with mean instructional depth increasing from 3.52 in 2016 to 3.69 in 2024, though this change was not statistically significant ($p = 0.41$). Vectorworks, Civil3D, and Revit showed minimal change across the two survey years, with none exhibiting statistically significant differences. In contrast, Land F/X demonstrated a substantial and statistically significant increase, rising from a mean of 0.36 in 2016 to 1.04 in 2024 ($p = 0.02$), indicating growing curricular emphasis on landscape-focused BIM-style workflows. ArcGIS also increased in instructional depth, rising from 2.40 to 2.96, though this change was not statistically significant ($p = 0.16$).

In the 2D rendering category, Adobe Photoshop continued to be one of the most deeply taught software packages, with mean scores increasing from 3.64 in 2016 to 3.88 in 2024, though this change was not statistically significant ($p = 0.08$). Adobe Illustrator exhibited a statistically significant increase, rising from 2.68 to 3.56 ($p < 0.01$), reinforcing its expanding role in graphic communication and visual representation within landscape architecture curricula.

The most pronounced shifts occurred in the 3D modeling category. Rhinoceros 3D (Rhino) showed a statistically significant increase in instructional depth, rising from 1.60 in 2016 to 2.67 in 2024 ($p = 0.01$). In contrast, SketchUp experienced a slight decrease, declining from 2.60 to 2.35, though this change was not statistically significant ($p = 0.39$). 3ds Max demonstrated a statistically significant decrease, dropping from 0.92 to 0.27 ($p < 0.01$), indicating a clear shift away from this platform in academic instruction.

Among 3D modeling plug-ins and rendering software, Lumion exhibited the largest increase across all software categories, rising from 0.08 in 2016 to 2.46 in 2024 ($p < 0.01$). Grasshopper showed a moderate increase, from 1.12 to 1.44, though this change was not statistically significant ($p = 0.29$), mirroring Rhino's rise and reinforcing the continued presence of computational and parametric design tools within landscape architecture curricula (AMOROSO et al. 2022). In contrast, V-Ray decreased from 0.80 to 0.40, though this change was not statistically significant ($p = 0.10$). Kerkythea declined to a mean of 0.00 by 2024, while Podium showed a statistically significant decrease, dropping from 0.28 to 0.02 ($p < 0.01$).

In the desktop publishing category, Adobe InDesign remained consistently high, increasing from 3.40 in 2016 to 3.69 in 2024, though this change was not statistically significant ($p = 0.28$). Pages remained negligibly used across both survey years, with no meaningful change observed.

When asked about the structure of software instruction, 63% of programs in 2016 reported teaching software through specialized technology courses, with the remaining programs embedding instruction primarily within design studios. By 2024, this proportion increased to 79% of programs offering specialized technology courses, though this change was not statistically significant.

	Software Name, *Survey Year*	Mean	SD	*p*
2D Drafting and Spatial	AutoCAD, *2016*	3.52	0.71	0.41
	AutoCAD, *2024*	3.69	0.51	
	Vectorworks, *2016*	0.28	0.74	0.58
	Vectorworks, *2024*	0.27	0.54	
	Civil3d, *2016*	0.56	1.12	0.68
	Civil3d, *2024*	0.54	0.92	
	Revit, *2016*	0.56	1.23	0.56
	Revit, *2024*	0.50	0.90	
	Land F/X, *2016*	0.36	0.86	0.02
	Land F/X, *2024*	1.04	1.27	
	Microstation, *2016*	0.16	0.8	0.66
	Microstation, *2024*	0.02	0.14	
	ArcGIS, *2016*	2.40	1.50	0.16
	ArcGIS, *2024*	2.96	1.13	
	ArchiCAD, *2016*	0.16	0.80	0.62
	ArchiCAD, *2024*	0.10	0.43	
2D Rendering	Photoshop, *2016*	3.64	0.64	0.08
	Photoshop, *2024*	3.88	0.33	
	Illustrator, *2016*	2.68	1.49	< 0.01
	Illustrator, *2024*	3.56	0.71	
3D Modeling	Rhino, *2016*	1.60	1.68	0.01
	Rhino, *2024*	2.67	1.37	
	SketchUp, *2016*	2.60	1.73	0.39
	SketchUp, *2024*	2.35	1.70	
	3dsMax, *2016*	0.92	1.32	< 0.01
	3dsMax, *2024*	0.27	0.74	
	Maya, *2016*	0.08	0.28	0.52
	Maya, *2024*	0.06	0.32	
	Vue, *2016*	0.04	0.20	0.63
	Vue, *2024*	0.02	0.14	
3D Modeling Plug-ins	Lumion, *2016*	0.08	0.28	< 0.01
	Lumion, *2024*	2.46	1.44	
	Grasshopper, *2016*	1.12	1.42	0.29
	Grasshopper, *2024*	1.44	1.38	
	V-Ray, *2016*	0.80	1.12	0.10
	V-Ray, *2024*	0.40	0.82	
	Kerkythea, *2016*	0.12	0.44	0.05
	Kerkythea, *2024*	0.00	0.00	
	Podium, *2016*	0.28	0.61	< 0.01
	Podium, *2024*	0.02	0.14	
Desktop Publishing	InDesign, *2016*	3.40	1.04	0.28
	InDesign, *2024*	3.69	0.59	
	Pages, *2016*	0.04	0.20	0.97
	Pages, *2024*	0.04	0.20	

Fig. 1: Mean scores and standard deviation, along with the p-value from the Mann-Whitney U test for software in both the 2016 and 2024 surveys

4 Discussion

The survey trends reveal a dynamic software landscape that both reflects and shapes landscape architecture education and professional practice. The expansion in the number of software platforms taught, along with increased instructional depth, suggests that academic programs have elevated expectations for digital literacy. When contextualized alongside surveys conducted by ASLA (GEORGE & SUMMERLIN 2019), these findings indicate that software adoption in academia and practice exists in a state of reciprocal tension: universities often lead in exploring emerging tools, while professional demand reinforces the continued inclusion of others. The rise of Rhinoceros 3D (Rhino) over SketchUp exemplifies academia's forward-looking engagement with complex modeling and parametric workflows in an environment that allows for design exploration without the constraints of billable hours. Conversely, the increased adoption of Land F/X reflects direct influence from professional offices and internships, where efficiency and integration with construction documentation workflows are critical.

This reciprocal relationship is not new. Early surveys by PALMER (1994) emphasized the resource constraints and learning demands that limited early software integration, while TAI (2003) argued that the discipline's future depended on graduates who were both creative and technically proficient. Over time, this dual emphasis has matured into a pedagogical approach in which digital representation is viewed not as a distraction from design thinking, but as a catalyst for deeper inquiry and experimentation.

The results also point to a continuing cultural shift in how digital instruction is structured within academic programs. During the 2000s and early 2010s, many departments moved away from dedicated software courses in favor of embedding digital instruction within design studios (SUMMERLIN et al. 2017). The 2024 survey data indicate a reversal of this trend, with nearly 80% of programs now teaching digital tools through specialized technology courses, up from 63% in 2016. This shift reflects the growing complexity of digital workflows and the need for focused learning environments where students can develop technical proficiency before integrating tools into studio-based design work.

One notable outcome of the survey is that three of the four most deeply taught software platforms primarily support graphic communication rather than the generative act of design itself. This suggests that visual representation has become increasingly central within landscape architecture education. While this emphasis raises questions about whether programs are prioritizing polished imagery over design exploration, an alternative interpretation is that faculty continue to value analog methods, such as hand drawing, as essential components of the design process. In this context, instructional time devoted to analog exploration may compete with digital design development, while digital rendering has largely supplanted traditional hand-rendering as the primary mode of final representation.

The most substantial shifts occurred within the 3D modeling and rendering ecosystem. Rhino's rise as the most deeply taught modeling platform reflects a broader consolidation in this category, occurring alongside a modest decline in SketchUp and a more pronounced abandonment of 3ds Max. Rendering tools exhibited an even sharper realignment, with Lumion demonstrating the largest gains across all software categories while other renderers declined. These shifts suggest a preference for tools that balance visual quality with accessibility and workflow efficiency. Emerging platforms such as D5 Render, released in 2020,

may further disrupt this category in the future, though adoption within academic programs remained limited at the time of the 2024 survey.

The significant increase in Land F/X adoption points toward growing interest in BIM-informed workflows and software capable of bridging traditionally separate categories, particularly 2D drafting and 3D modeling. The lack of comparable growth in platforms such as Vectorworks and Revit is notable. Within U.S. programs, Land F/X appears to have positioned itself as a pragmatic solution that integrates BIM functionality while allowing users to remain within software ecosystems that are already well established, such as AutoCAD and, increasingly, Rhino.

The emergence of artificial intelligence further underscores the rapid evolution of digital pedagogy in landscape architecture. Although AI integration within the 2024 survey was limited, more recent research suggests adoption has accelerated substantially (BRAIDEN et al. 2025). AI's presence across both embedded tools and standalone applications highlights its adaptability to tasks including visualization, analysis, and generative design. As Fernberg and Chamberlain (2023) note, these developments raise important questions related to authorship, process, and creativity in design education.

Finally, this longitudinal analysis reinforces STEFFENS' (2017) observation that software ecosystems tend to expand rather than compete. The increase in total software taught, rather than wholesale replacement of existing tools, indicates that digital education in landscape architecture is becoming more diversified and specialized. As this complexity increases, the role of faculty may shift toward curating software ecosystems and guiding students in making informed choices, rather than teaching proficiency in a fixed set of platforms.

5 Conclusion and Outlook

Over the past eight years, software instruction in landscape architecture programs has evolved in both scope and sophistication. This longitudinal analysis demonstrates that academic programs have not only responded to shifts in professional practice but, in several cases, anticipated them by integrating emerging tools and workflows ahead of widespread adoption. As a result, digital instruction has become increasingly layered and embedded across multiple stages of the design process.

Taken together, the results underscore that digital fluency is no longer a supplemental skill within landscape architecture curricula. Proficiency across drafting, modeling, rendering, and publishing platforms has become foundational to contemporary education and practice. At the same time, the expansion of software ecosystems presents challenges for curricular coherence, instructional depth, and student accessibility, suggesting that educators may increasingly focus on cultivating adaptable workflows rather than mastery of individual platforms.

This study also highlights questions that extend beyond the scope of the current survey. While the analysis captures trends in digital software instruction, it does not account for how analog design methods are positioned within curricula or how they intersect with digital workflows. Future research may benefit from examining how programs balance analog and digital approaches to design thinking, and whether emphasis is placed on process, product, or a combination of both.

As new technologies continue to emerge, particularly in areas such as artificial intelligence and computational design, longitudinal studies will remain essential for understanding how landscape architecture education adapts to rapid technological change. By documenting shifts over time, this research contributes to an ongoing conversation about how digital tools shape pedagogy, professional preparation, and the evolving identity of the discipline.

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Task-Technology Fitting 3D Reconstruction Methods in Landscape Architecture

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Abstract: Three-dimensional (3D) reconstruction has become a foundational component of landscape architecture and planning workflows. Yet despite decades of technical maturity, industry adoption remains uneven. This paper aims to address that gap by providing an intuitive prioritization framework for fitting 3D method to design/planning task. It includes a comparative review of four major 3D reconstruction approaches – Structure-from-Motion (SfM) photogrammetry, LiDAR, Neural Radiance Fields (NeRF), and 3D Gaussian Splatting (3DGS) – evaluated through both technical performance and design process affordances, and a mapping of the methods across modalities of landscape practice. Where legacy approaches champion spatial precision, emerging neural methods are positioned to reframe 3D capture as not just documentation but immersive, design-integrated interpretation.

Keywords: 3D reconstruction, photogrammetry, LiDAR, neural rendering, neural radiance fields, 3D Gaussian splatting, immersive visualization, landscape architecture

1 Introduction

Producing 3D data and geometry with images and point clouds is now a staple in architecture, engineering and the construction (AEC) industry, and is utilized in landscape architecture and planning for tasks spanning site analysis, visualization, and stakeholder engagement all the way through construction and post-occupancy evaluation (URECH et al. 2022, SEDLÁČEK et al. 2020, MILLIGAN 2019). However, in the case of both design and construction, these established 3D reconstruction methods are ubiquitously known but not necessarily ubiquitously used. High costs or training needs (ALSAMARRAIE et al. 2022), project time constraints, or lack of tools or knowledge base to overcome issues such as performance degradation in areas with low texture, occlusions, water, or complex vegetation (WESTOBY et al. 2012), among other factors (BAUGUS et al. 2025), seem to have contributed to a lagging industry adoption rate, despite a well-established literature and training pipeline in academia (SUMMERLIN & GEORGE 2024).

What could bridge the constraints gap between knowledge of 3D reconstruction methods and their enhancement of landscape practice? Recent breakthroughs in computer vision – particularly Neural Radiance Fields (NeRF) and 3D Gaussian Splatting (3DGS) – have introduced image-based rendering approaches that might offer this transformative potential. These newer methods claim faster, more visually immersive outputs than legacy workflows (SCHOB & REKITTKE 2023). Yet while corroboration of those claims is limited in design and planning, there is a sufficient saturation of studies across 3D reconstruction methods to begin to segment their perceived effectiveness. This paper presents a comparison of SfM, LiDAR, NeRF, and 3DGS, mapping each technique according to its observed technical performance and relevant landscape architecture and planning workflows. In more specific terms, we explore four questions: 1) What is different about emerging 3D reconstruction methods when compared to legacy methods? 2) What are the comparative workflow and performance tradeoffs between 3D reconstruction methods? 3) Do the affordances of emerging techniques or the

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advances in established ones offer better pathways to overcome adoption barriers in industry? And 4) Do the affordances of emerging techniques signal future transformations in design and planning workflows? This work is neither a systematic review nor empirical investigation. Rather it proposes a simple decision framework, grounded in literature, to provoke digital landscape architecture researchers and practitioners to think more deeply about the future of 3D reality capture and modelling; in particular, how to build common benchmarks for assessing what Goodhue and Thompson (1995) would call the right "task-technology fit" in a rapidly advancing 3D reconstruction ecosystem.

2 Review of 3D Reconstruction Techniques

In the case of the first question, it is important to review each 3D method, including its core components, key workflows, and the state of the art in landscape and planning practice. What follows is a narrative review drawn from literature searches in JoDLA, Scopus, and Google Scholar, and industry news publications for articles published in the last 25 years focused on SfM, LiDAR, NeRF, or 3DGS. To be included in our analysis, articles needed to feature at least one 3D method, at least one relevant field or application to landscape architecture, and have discussion on technical strengths and limitations of the method for a given task.

2.1 Structure-from-Motion (SfM) Photogrammetry

Structure-from-Motion (SfM) emerged as a transformative photogrammetric technique to create 3D geometry from 2D images. Its foundational moment in the geosciences is attributed to Westoby et al. (2012), who demonstrated how consumer-grade cameras and open-source software could deliver high-resolution topographic models rivaling traditional survey methods, sparking widespread interest across environmental disciplines. Subsequent technical improvements came from Schönberger and Frahm (2016), whose contribution restructured the SfM pipeline for improved robustness and scalability. Their work, including the widely used COLMAP software, enabled more reliable feature matching and bundle adjustment, streamlining the reconstruction of large or complex scenes. Together with advancements in several other disciplines, these developments solidified SfM as a cornerstone technique in terrain modeling, bolstered by its flexibility, low cost, and ease of deployment. SfM's accessible workflow has also catalysed a wave of applications in landscape architecture and environmental monitoring. Smith et al. (2016) highlighted how SfM revolutionized topographic surveying in physical geography, while Iglhaut et al. (2019) reviewed its increasing role in forestry for canopy structure analysis and biomass estimation. In practice, SfM has been deployed for ecological restoration monitoring (e. g., tidal marshes) and integrated into landscape architecture education to support site analysis and participatory design workflows. Sedláček et al. (2020) described how point clouds derived from UAV-based SfM became a hybrid medium between cartography and photography, offering students and professionals a new lens for spatial interpretation.

2.2 LiDAR

LiDAR technology has long served as a benchmark for precision 3D data acquisition, with Wehr and Lohr (1999) offering a foundational technical overview of airborne laser scanning for terrain modeling. Unlike passive methods such as SfM, LiDAR provides active range measurements, allowing for dense and accurate 3D point clouds even under canopy cover.

Over time, the field has progressed from static terrestrial systems to mobile and drone-mounted platforms (GEORGE & PARK 2020). MAEDA et al. (2025) emphasized the rapid maturation of terrestrial laser scanning (TLS), highlighting improvements in resolution, cost, and AI-driven post-processing. As TLS becomes more portable and accessible, LiDAR continues to set the standard for capturing accurate surface and vegetation structure, enabling its integration into workflows requiring digital twins and ecological analytics. LiDAR's operational value in landscape and environmental planning is well-established across domains such as forestry, urban design, and heritage conservation. In forestry, it enables accurate mapping of canopy structure, tree height, and biomass. Cheng et al. (2025) used LiDAR for detailed visibility analysis in urban parks, improving spatial design through more precise sightline evaluations. In the design disciplines, Milligan (2019) introduced a theoretical lens on how LiDAR and drone-derived terrains mediate designers' relationships with site and representation. Sedláček et al. (2020) and Urech et al. (2022) extended these insights into teaching and practice, using LiDAR-derived point clouds to ground terrain manipulation in studio workflows. Collectively, these applications illustrate LiDAR's unique ability to enrich site documentation and interaction, especially in topographically complex or vegetated environments. It is also typically a more expensive method of capture.

2.3 Neural Radiance Fields (NeRF)

Neural Radiance Fields (NeRF), introduced by Mildenhall et al. (2020), marked a paradigm shift in 3D reconstruction by encoding scene geometry and appearance in a neural network rather than explicit geometry. Using volumetric rendering and a continuous 5D function (3D location and 2D viewing direction), NeRF achieved photorealistic novel view synthesis, setting a new benchmark in visual fidelity. However, early implementations were computationally intensive. Müller et al. (2022) addressed this limitation through Instant-NGP, a multi-resolution hash-grid encoding that enabled real-time rendering and rapid training, drastically lowering barriers to use. Extensions such as Block-NeRF (TANCIK et al. 2022) further scaled this technique to urban contexts by tiling radiance fields into city-scale environments. These advances have accelerated NeRF's transition from a computational novelty to a practical tool for immersive 3D capture. While NeRF is still emerging in environmental workflows, early studies suggest transformative potential. VASILJEVIĆ et al. (2025) applied NeRF to architectural heritage preservation, finding that it handled reflective and translucent surfaces better than traditional photogrammetry. In the design context, Schob and Rekittke (2023) explored its speculative use in landscape architecture, arguing that NeRF could create richly immersive site visualizations from minimal image data. NeRF's capacity to capture lighting and texture nuances opens new avenues for participatory design and stakeholder engagement. An industry news publication Geo Week reported growing interest in NeRF within AEC sectors in the most recent worldwide conference on 3D tech in AEC, noting its speed, accessibility, and integration potential with AR/VR tools (COLLINS 2025). Although NeRF currently lacks metric accuracy and GIS integration, its photorealism and real-time capability suggest it could complement existing methods in visualization-heavy stages of the planning and design process (SCHOB & REKITTKE 2023).

2.4 3D Gaussian Splatting (3DGS)

3D Gaussian Splatting (3DGS), introduced by Kerbl et al. (2023), builds upon NeRF's goals while departing from its neural-heavy architecture. Instead of learning a radiance field im-

plicitly, 3DGS represents scenes as a cloud of elliptical Gaussians, each with position, opacity, and appearance attributes. These splats are rendered using a rasterization pipeline that enables real-time novel view synthesis at high resolutions and frame rates. The method starts with a sparse SfM-derived point cloud and optimizes splats' geometry and shading in parallel. As noted in Bao et al. (2025), this explicit representation not only reduces computational cost but also improves rendering speed dramatically – offering 30+ FPS on consumer GPUs. The field is evolving rapidly, with enhancements aimed at supporting dynamic scenes, hybrid mesh-splat approaches, and potential editing capabilities. Although 3DGS is still in its infancy, its practical affordances for design and planning are already being explored. The Geo Week News (2025) report also notes that professionals in AEC and surveying are beginning to experiment with 3DGS for site visualization, attracted by its low computational burden and ease of deployment. Unlike NeRF, which often requires dense imagery and GPU time, 3DGS can operate efficiently on sparser data and render interactively. While no published environmental or landscape-specific case studies exist yet, the method's capacity for real-time rendering, rich photorealism, and scene navigability points toward promising use cases in stakeholder engagement, concept design, and immersive site analysis. As software tools mature, 3DGS may become a lightweight but powerful complement to heavier reconstruction pipelines.

3 Which Method, Which Workflow? Analyzing Task Fit and Trade-Offs

To answer the question of relative performance strengths and trade-offs, we offer two sets of parameters with which to evaluate 3D reconstruction methods for landscape architecture and planning workflows: technical performance and design tasks and modalities. In the case of technical performance, both the foundational literature introducing each method and subsequent case studies describe their advantages and limitations in a general sense. When translating that knowledge to design and planning practice, however, it is necessary to contextualize trade-offs according to specific needs within design and planning process.

3.1 Visual Truth vs Geometric Truth

Evaluative Question (s): What is the level of spatial accuracy of the model? (geometric truth) How authentic or immersive is the experience of the model? (visual truth)

Technical comparisons in computer vision often rely on Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index (SSIM) to measure reconstruction fidelity. However, as these are "pixel-wise" comparisons, they do not always reflect human perception or the structural integrity of a scene. Modern evaluations increasingly utilize Learned Perceptual Image Patch Similarity (LPIPS), which uses neural networks to better mimic human judgment of "blurry" or "ghosting" artifacts common in Neural Radiance Fields (NeRF) (MILDENHALL et al. 2021). For landscape architecture, a critical failure point is scale inconsistency or "metric drift". While LiDAR provides native, absolute metric scale, methods like SfM, NeRF, and 3DGS are inherently scale-ambiguous. Without constraints from Ground Control Points (GCPs) or fusion with LiDAR odometry, these methods may fail to maintain relative consistency across a scene. Ensuring a 1:1 metric relationship with the real world remains essential for tasks like grading plans and hydrologic surface modeling (WESTOBY et al. 2012).

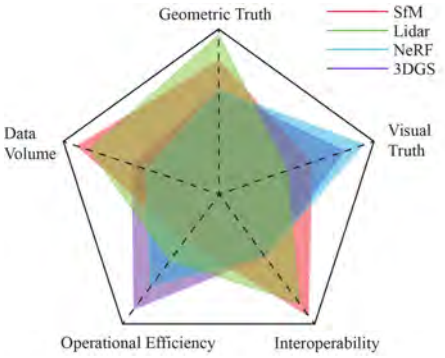

Fig. 1:
Comparative Technical Performance of 3D Reconstruction Methods

3.2 Operational Efficiency

Evaluative Question (s): How computationally intensive is reconstruction?

The choice between methods also hinges on the computational lifecycle, specifically training time (initial scene learning) and inference/rendering time (generating views after the camera pose is altered). Traditional SfM is computationally intensive during the "bundle adjustment" phase but generates relatively lightweight, interoperable point clouds. In contrast, 3D Gaussian Splatting (3DGS) offers a revolutionary shift, with training times measured in minutes rather than the hours required for traditional NeRF, alongside real-time inference speeds exceeding 30 FPS on consumer GPUs (KERBL et al. 2023).

3.3 Data Volume

Evaluative Question (s): How much data is needed for acceptable outputs?

3DGS' computational performance comes at the cost of data volume and robustness to limited datasets. 3DGS can generate massive .PLY files, whereas a NeRF "model" consists of highly compressed neural weights. Furthermore, the robustness of these methods varies significantly when data is sparse, a critical consideration for rapid environmental assessment during natural disasters where comprehensive image capture is difficult.

3.4 Interoperability

Evaluative Question (s): How broadly can the outputs integrate across software?

A significant hurdle for practitioners remains interoperability. Most standard CAD and BIM ecosystems cannot natively render radiance fields or Gaussian splats. To be utilized in a professional pipeline, these neural representations must be converted into manifold meshes or standardized point clouds. This conversion often introduces reconstruction error and sacrifices the photorealism that makes NeRF and 3DGS ideal for stakeholder engagement and VR walkthroughs. Ultimately, while 3DGS and NeRF excel in visualization-heavy stages and participatory design, LiDAR and SfM remain the industry standards for documentation requiring measurable outputs, legal veracity, or GIS integration (Fig. 1).

3.5 How to Contextualize Technical Performance in Design Process

Perhaps the most important complication when comparing 3D reconstruction methods is the fact that the relative importance of any given technical performance metric changes accord-

ing to task context (Fig. 2). For example, when engaging in site inventory and analysis or stakeholder engagement activities, providing a digital context model with survey grade geometry is welcomed, but it is most important to have a base model with visual continuity so that the designer or the stakeholders can interact with it and feel authentically, spatially connected to the place. Therefore, the relative weight of visual truth is much higher than that of geometric truth. Furthermore, the process of collecting site information, whether through smartphone imagery, UAV flyovers, or simply making sketches during a site walk, the relative ease of that data collection is much more important than whether that data ends up in a certain kind of software environment. The designer needs their tools to be quick, flexible, and easy to use. Similarly, when a designer is in the throes of conceptual development or iterating site design, they want a lean, visually immersive, and easy to use digital model that allows them to iterate in 3D without getting bogged down.

On the other hand, when a designer is going into a site documentation phase, whether for geospatial analysis or preparing construction documents that are legally binding, the importance of geometric truth, and accuracy cannot be overstated; nor can the weight of in-

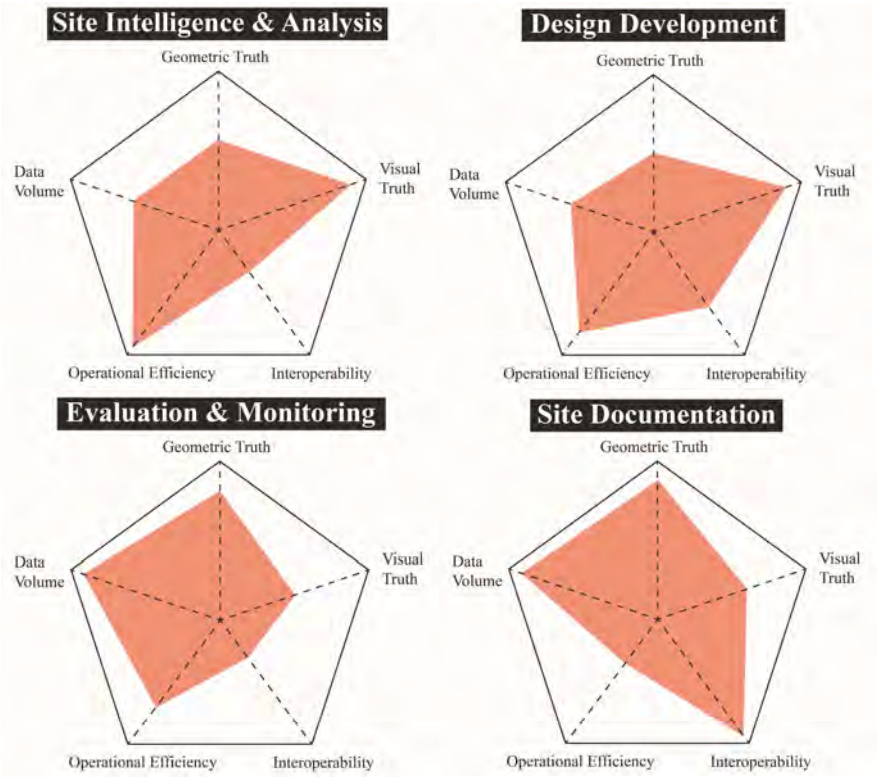

Fig. 2: Radar charts representing relative importance of performance metrics according to design modality. Each modality encompasses a range of tasks with similar performance needs.

teroperability of that site data be ignored since it is key for collaborating with the project team. The aesthetic or visual quality of the governing 3D/BIM model or the agility of the program being used to operate it are of much less importance. In the case of post-occupancy evaluation or long-term monitoring of a site, the most important weights would be in a combination of high geometric truth, and efficient management of data volume so that the monitoring activities can be done over and over again without becoming too unwieldy to manage. Also, because design workflows play a much less prominent role in evaluation or monitoring activities, the interoperability of data collection platforms with design software is not as integral. Figure 2 shows examples of how one might distribute or weight the importance of technical performance according to the context of a given design task or modality. Together with the overlay of comparative technical performance of each 3D reconstruction method (Fig. 1), these charts provide a sort of visual decision tree for how to choose and prioritize a 3D reconstruction method according to the needs of the task at hand.

4 Can Affordances Afford More Adoption?

Industry adoption of 3D site modeling in landscape architecture and planning has long been constrained by cost, expertise, and workflow complexity. Traditional photogrammetry and LiDAR provide high geometric accuracy but often require specialized equipment, training, and time-intensive processing, limiting their routine use in design practice (BAUGUS et al. 2025). Even drone-based photogrammetry – while lowering some barriers – still demands careful workflow integration and technical literacy that many firms struggle to sustain (BAUGUS et al. 2025).

Recent advances in neural reconstruction methods offer alternative affordances that may help bridge these gaps. Neural Radiance Fields (NeRF) and 3D Gaussian Splatting (3DGS) rely on image-only inputs, avoiding specialized sensors while succeeding in conditions that frequently confound feature-based photogrammetry. NeRF's view-dependent scene representation, for example, has been shown to reconstruct reflective, transparent, or weakly textured surfaces with greater visual continuity than traditional methods, while photogrammetry remains superior on well-textured, matte surfaces – rendering the approaches complementary rather than competitive (REMONDINO et al. 2023). A key distinction lies in output form: NeRF and 3DGS prioritize immersive, visually coherent representations over strict metric fidelity. In particular, 3DGS trades minor geometric detail for real-time rendering performance, enabling interactive exploration that was previously impractical with slower SfM or NeRF pipelines.

These affordances might shift emphasis away from precision surveying that is outsourced or decoupled from design process toward rapid, in-house automated production of experiential 3D environments that can be utilized from the moment designers are on site and later supplemented by precision surveys through documentation phases. For many landscape and planning workflows – early-stage site understanding, design communication, and stakeholder engagement – such visual legibility may outweigh sub-centimeter accuracy. Meanwhile, established techniques continue to evolve. Integrated workflows combining UAV photogrammetry and LiDAR now leverage the strengths of each, using LiDAR for dense vegetation and photogrammetry for high-fidelity textures (BAUGUS et al. 2025). Taken together, emerging neural methods and refined traditional approaches suggest a context-driven decision framework in which practitioners select or combine tools based on task-specific needs. Rather than

replacing legacy methods, neural techniques expand the range of conditions under which image-based 3D capture becomes practical and usable within design workflows.

5 Emerging Realities and Future Work

Beyond lowering adoption barriers, the affordances of NeRF and 3DGS point toward broader transformations in how landscapes are represented, interpreted, and communicated. Unlike point clouds or polygonal meshes, neural scene representations encode view-dependent appearance and illumination, producing photorealistic environments that can be navigated much like virtual site visits. This immersive realism directly supports user-centered outcomes, enabling planners, designers, and stakeholders to experience captured environments with lighting and material responses that more closely approximate real-world perception. Evidence from adjacent domains such as cultural heritage studies demonstrate that neural reconstructions improve interactive performance, perceptual realism, and communicative value in visually complex environments where traditional models degrade (MAZZACCA et al. 2023, REMONDINO et al. 2023), which could open new possibilities for landscape architects in documentation, visualization, and public engagement.

At the same time, this review underscores that no single reconstruction method satisfies all design and planning needs. A fundamental divergence persists between geometric truth – essential for grading, engineering, and construction – and visual truth, which underpins engagement, atmosphere, and experiential understanding. Rather than pursuing a monolithic solution, the evidence points toward hybrid workflows that leverage shared input data to generate complementary outputs. A single drone survey, for instance, may feed an SfM pipeline to produce accurate terrain geometry while simultaneously training a NeRF or 3DGS model for immersive walkthroughs. In such configurations, LiDAR remains indispensable for large-scale terrain mapping or dense vegetation, acting as a metric anchor for visually richer but geometrically ambiguous neural representations. Despite this promise, systemic challenges remain. Neural representations lack standardized formats for direct integration into CAD, BIM, and GIS environments, and converting radiance fields or Gaussian splats into manipulable design surfaces often introduces error or undermines their visual advantages. Computational demands and GPU requirements also exceed current norms in many landscape architecture firms. These barriers are surmountable but will require targeted tool development, interoperability standards, and expanded technical literacy within the profession. Ultimately, the significance of NeRF and 3DGS lies not only in technical performance but in their potential to reposition 3D capture within the design process – from an underutilized and unintentionally peripheral documentation task to an interactive, interpretive medium. If neural methods can mature into interoperable components of broader design ecosystems, they may help close the long-standing gap between research knowledge and practical uptake. In doing so, they offer a pathway toward richer, more experiential forms of landscape analysis, design, and planning – reshaping how professionals conceive of, communicate, and work with site information.

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Urban Heat, Thermal Comfort and Microclimate

Quantifying Urban Heat Island Mitigation by Green Roofs Through Soil-Informed Hygrothermal Performance Modeling

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Abstract: Green roofs reduce urban heat through evapotranspiration, substrate insulation, and thermal mass buffering - mechanisms that all depend on dynamic soil volumetric water content (VWC). Yet mainstream tools such as the Urban Weather Generator (UWG) and EnergyPlus treat substrate moisture and thermal properties as fixed. This study proposes a soil-informed hygrothermal performance framework comprising: (1) a GRU-based sequential model outperforming tree-based baselines by 26.9% in R^2, trained on monitored green roof data to predict hourly VWC, (2) a physically consistent VWCUWG coupling scheme activating both solar and VPD-driven evaporation pathways, and (3) analytical quantification of VWC-induced thermal property errors in EnergyPlus. Results show that antecedent soil moisture memory and air temperature emerge as dominant VWC drivers. Dynamic coupling reduces summer daytime roof surface temperature by a mean of 1.812 °C, with an additional nighttime component of −0.34 °C from the VPD pathway absent in solar-only models. Static substrate assumptions underestimate volumetric heat capacity by 96.5%, causing a 77% overestimate of interior temperature amplitude and a 2.2-hour phase error in peak cooling load timing. Spatial scaling across 287 Manhattan census tracts reveals cooling potential of −0.15 to −1.42 °C governed by building density, with existing green roof coverage below 2% of full-greening potential. The framework offers a scalable basis for performance-informed green roof design at the urban scale.

Keywords: Urban heat island, green roof, soil moisture, energy modeling, nature-based solution

1 Introduction

Rapid urbanization has reshaped urban energy-water balances by replacing permeable, vegetated surfaces with impervious materials, amplifying sensible heat storage and suppressing evapotranspiration processes that intensify Urban Heat Island (UHI) risk and associated cooling-energy demand. Urban green infrastructure (UGI) is widely regarded as a mitigation strategy, yet its cooling effectiveness varies across spatial and climatic contexts (WONG et al. 2021, CHEN et al. 2026). Recent evidence shows that spatial configuration, including green-patch arrangement and connectivity, can be as influential as total green quantity in shaping air temperature, especially in dense fabrics (BEELE et al. 2024, ZHANG et al. 2025).

Among UGI options, green roofs are particularly attractive because they repurpose extensive roof areas into thermally active landscapes where shading, insulation, and evapotranspiration can jointly reduce roof surface temperatures and contribute to canopy-scale cooling. Beyond heat mitigation, emerging typologies such as garden rooftop farms introduce a dual value proposition by coupling microclimate regulation with spatial productivity, highlighting the relevance of performance-based landscape design to compact cities (DONG et al. 2025). Empirical and simulation-based studies have further quantified the thermal and energy performance of green roofs under real climatic conditions, highlighting their measurable cooling

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and energy-saving potential while also revealing sensitivity to operational and environmental variability (MUTANI & TODESCHI 2020).

However, a persistent limitation in green-roof UHI studies lies in the hydrological realism of mainstream simulation workflows. Many urban climate and building energy tools still describe green roofs using static thermal properties or fixed evaporation efficiencies, implicitly assuming sustained moisture availability. In practice, green-roof cooling is moisture-limited: substrate volumetric water content (VWC) evolves with rainfall, antecedent dry periods, and atmospheric demand, and its dynamics directly govern latent heat flux as well as moisture-dependent thermal conductivity and heat capacity. Recent building-energy research has explicitly shown that ignoring moisture effects can bias energy-model predictions, underscoring the need to incorporate moisture – thermal coupling rather than treating substrate properties as constants (WANG et al. 2025).

Taken together, these challenges reveal a methodological gap between detailed hygrothermal understanding and scalable urban-climate evaluation. Bridging this divide requires approaches that integrate data-driven learning, physical interpretability, and spatial explicitness within a coherent simulation pipeline. By reframing green-roof performance through moisture-informed modeling and cross-scale translation, this study advances a performance-based paradigm for climate-responsive landscape systems at the urban scale – aligning environmental intelligence with the emerging frontier of computational design and climate analytics.

2 Conceptual Framework

Green-roof cooling emerges from tightly coupled hydrological–thermal processes, yet common urban workflows still treat soil moisture as static – disconnecting evapotranspiration and moisture-dependent substrate properties from canyon-scale outcomes. Therefore, this study proposes a soil-informed hygrothermal performance framework that links hourly VWC dynamics to Urban Weather Generator (UWG) energy partitioning and building-physics implications, and then scales results to real Manhattan morphology, as shown in Figure 1.

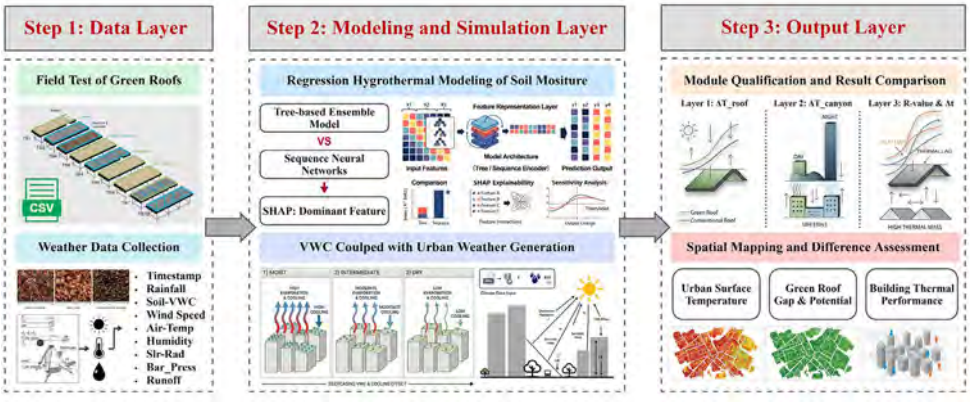

Fig. 1: Research framework of this study

This study follows a hybrid, multi-scale pipeline:

1) Moisture prediction: Train time-series models compared with tree-based algorithms on long-term monitored green-roof environmental data to generate hourly VWC sequences.
2) Climate transfer: Apply the trained GRU model to the New York EPW file forcing to produce a 8760-hour VWC series of green roof soil moisture for downtown Manhattan.
3) Hygrothermal module: Inject VWC into UWG via physically consistent evaporation correction, and quantify thermal property errors under static EnergyPlus assumptions.
4) Spatial scaling: Map tract-level green roof cooling potential across 287 Manhattan census tracts using morphology-based scaling and observed surface temperature context.

3 Material and Methodology

3.1 Study Location and Date Collection

This study selects Manhattan (New York City, climate zone 4A) as a representative high-density urban prototype characterized by mid-rise canyons (30-50 m), high building coverage (density $\approx$ 0.65), and limited ground vegetation. Such morphology intensifies summer UHI effects, making roof-level interventions critical for surface energy redistribution.

Model development relies on a five-year monitored dataset from the Sheffield Hadfield green roof, configured with a lightweight Heather with Lavender Substrate (HLS) and Sedum vegetation. This extensive system offers a well-documented empirical basis for green roof hydrological performance dynamics (STOVIN et al. 2015). The trained moisture-response model is subsequently driven by Manhattan climate inputs to estimate hourly substrate moisture for urban-scale hygrothermal coupling.

3.2 Hygrothermal Modeling of Green Roof

Building upon the curated hourly dataset and variable definitions, green-roof substrate moisture was modeled as a data-driven hygrothermal surrogate to represent moisture-dependent thermal regulation. Previous research demonstrates that machine-learning approaches, such as artificial neural networks (ANN), can effectively reproduce complex green roof hydrological–thermal interactions under dynamic meteorological forcing (ASADI et al. 2020). Here, the target variable is hourly VWC of green roof bed, denoted as θ_t. The predictive structure is formulated as:

$$\theta_t = f(\theta_{t-1}, x_t), \quad x_t = \{WS_t, T_{air,t}, RH_t, Slr_t, BP_t, RG_t\}$$

where WS is wind speed, T_{air} is air temperature, RH is relative humidity, Slr is solar radiation, BP is barometric pressure, and RG is hourly rainfall.

To evaluate alternative representations of $f(\cdot)$, six models were implemented under a time-aware training protocol: three tree-based ensemble regressors using lagged moisture as an explicit predictor, and three sequence neural networks learning temporal dependencies from fixed-length hourly input windows. This comparative framework establishes a robust surrogate basis for subsequent hygrothermal coupling analysis.

3.3 Urban Energy Balance Mechanism

The UWG integrates UHI processes into building-energy workflows by resolving canyon-scale sensible-latent exchange under prescribed morphology (NAKANO et al. 2015). In its default configuration, green-roof evaporation is weakly coupled to canyon air because soil moisture storage and VPD-driven evaporation remain effectively inactive. Here, hourly predicted VWC is introduced as an explicit moisture state variable to regulate roof surface energy partitioning – recognizing roof temperature as the first-order cooling response (Fig. 2). Soil evaporation is computed through a stress-modulated aerodynamic formulation:

$$Q_{lat,t}^{soil} = \beta_{\text{soil}}(VWC_t)\left(1 - f_{\text{veg}}\right) E_{\text{open}}\, \rho_w\, \lambda_v$$

Where β_{soil} denotes the Noilhan – Planton moisture stress function and $(1 - f_{\text{veg}})$ represents exposed substrate fraction. The corrected latent flux modifies the roof sensible – latent balance, reducing surface temperature, and is subsequently incorporated into the canyon moisture budget, enabling soil-driven cooling to propagate to secondary air-temperature responses.

At the building scale, moisture-dependent substrate properties are dynamically evaluated to quantify thermal-mass bias under static EnergyPlus in HB-Vegetation Material component of Ladybug Tools. Thermal conductivity and volumetric heat capacity are updated as:

$$k(\theta) = k_{dry} + f(\theta, k_{sat}), \quad C_{vol}(\theta) = \rho_b c_{dry} + \theta \rho_w c_w$$

These parameters are further propagated into periodic heat-transfer indicators, including thermal resistance, decrement factor, and phase lag, enabling direct estimation of amplitude attenuation and timing errors induced by fixed-property green-roof models.

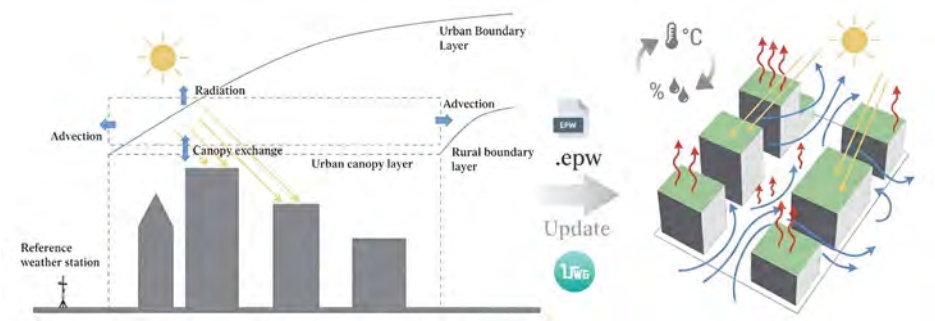

Fig. 2: Schematic diagram of urban weather generation mechanism

3.4 Spatial Mapping and Assessment

Hygrothermal cooling was spatially extrapolated to 287 Manhattan census tracts using a morphology-based scaling approach anchored to the single-point VWC-UWG simulation (bldDensity = 0.65; vegroof = 0.75). Tract-level cooling was estimated as ΔT_tract = ΔT_ref × (ρ_bld / 0.65), where ρ_bld denotes the building footprint – to – lot-area ratio derived from MapPLUTO v24 under a full-greening scenario. Observed UHI intensity was obtained from Landsat 8 summer surface temperature composites (2020-2022), and existing green roof cov-

erage from the Treglia inventory. This parametric transfer enables tract-scale evaluation of cooling magnitude and intervention priority without additional UWG simulations.

4 Results and Discussion

4.1 Soil Moisture Dynamics Prediction

Hourly meteorological drivers were paired with cyclic time encodings to represent both instantaneous forcing and seasonal context. The Pearson correlation matrix (Fig. 3) indicates that VWC increases with relative humidity and barometric pressure, while decreasing most strongly with air temperature and, to a lesser extent, solar radiation, consistent with a substrate state governed by atmospheric drying demand and synoptic moisture conditions.

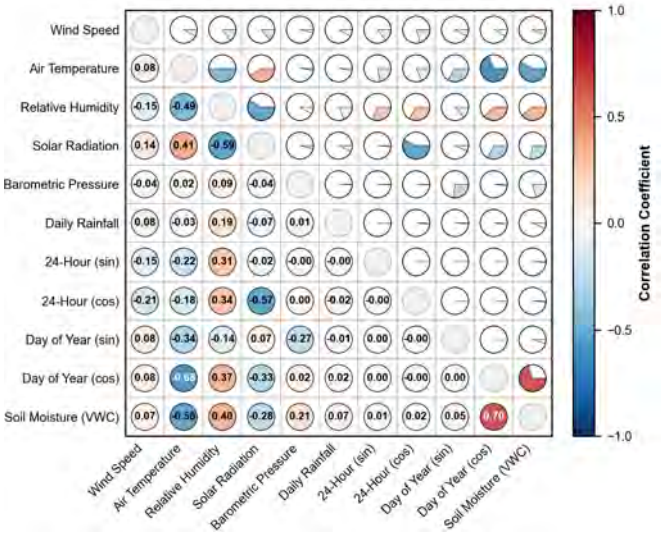

Fig. 3:
Environmental and temporal variables for soil moisture in feature correlation matrix

Model benchmarking (Tab. 1) demonstrates a marked performance gap between sequence-aware and tree-based approaches. Compared with the XGBoost model, the GRU model improves test R^2 by 26.9% and reduces MAE by 25.0%, indicating substantially enhanced predictive fidelity. These gains stem from the GRU's gated recurrent structure, which preserves antecedent moisture states and encodes temporal dependency, whereas tree ensembles primarily lack an explicit memory mechanism for cumulative hydrological processes.

To preserve causality, the five-year record was partitioned into chronologically ordered blocks for training, validation, and final testing. Each forecast used a rolling 2-week history window as input, enabling the GRU model to learn delayed recharge – drainage responses. The resulting trajectories (Fig. 4) reproduce both seasonal envelopes and event-scale pulses: rainfall episodes trigger rapid wetting followed by multi-day dry-down, and the model maintains continuity across the train/test boundary with limited amplitude damping – consistent with a system dominated by cumulative water balance rather than single-hour forcing.

Table 1: Performance comparison of different regression models

Model Name	Test R^2	Test MAE	Test MAPE	Model Type
GRU	0.819	0.030	0.126	Sequence Model
CNN-LSTM	0.742	0.037	0.168	Sequence Model
LSTM-Attention	0.725	0.036	0.154	Sequence Model
XGBoost	0.645	0.040	0.189	Tree-based Model
LightGBM	0.644	0.040	0.188	Tree-based Model
Random Forest	0.644	0.038	0.179	Tree-based Model

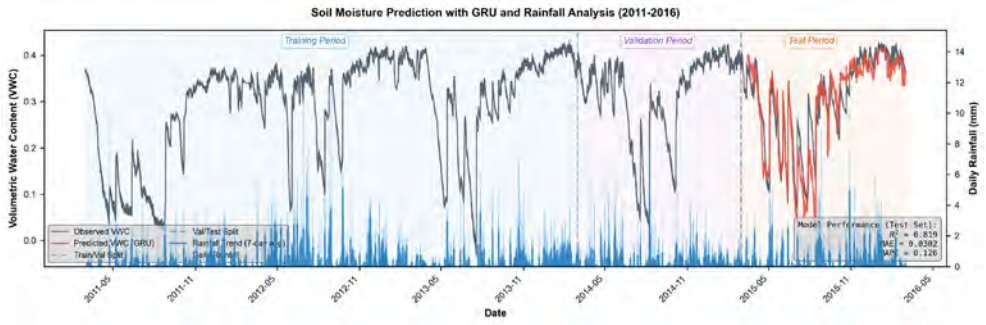

Fig. 4: Time-series prediction of soil moisture with GRU model

4.2 Explainable Sensitivity Analysis

Shapley Additive exPlanations (SHAP) is a post-hoc, model-agnostic attribution method that decomposes predictions into additive feature contributions. Applied to the GRU model (Fig. 5), SHAP reveals that lagged VWC memory affected by time is the strongest positive driver, while higher air temperature contributes negative effects through enhanced evapotranspiration. Secondary controls are rainfall intensity and relative humidity, aligning with the physical water-balance mechanism of green-roof moisture. It is worth noting that solar radiation has the least impact on VWC. This might be due to the shading effect of the vegetation layer, which counteracts the evaporation feedback, resulting in a non-linear effect.

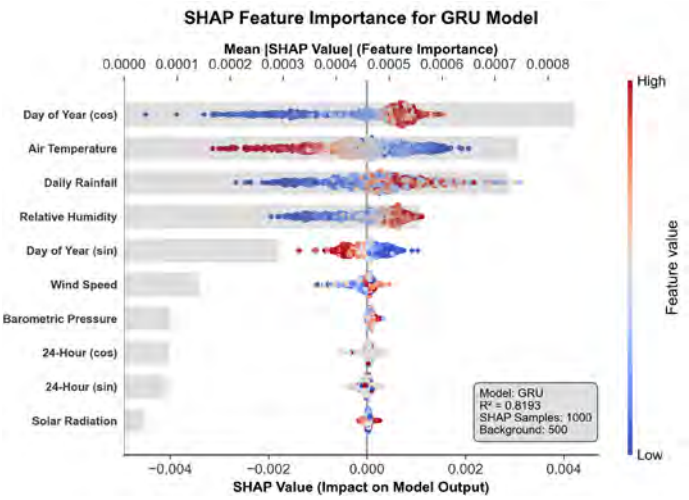

Fig. 5: Input variables' SHAP feature importance analysis for GRU model

4.3 Coupling Module Effectiveness

In the default UWG configuration, evapotranspiration efficiency is fixed (grassFLat = 0.40), the VPD-driven bare-soil evaporation branch is disabled (waterStorage = 0), and substrate thermal properties remain static at the Honeybee Vegetation Material reference values (k = 0.35 W/m-K, C_vol = 1,320 kJ/m³-K). These assumptions decouple roof latent flux from actual moisture state, leaving both the VPD evaporation pathway and moisture-driven thermal mass variations unrepresented. The VWC-UWG V3 architecture corrects this through a post-SurfFlux Noilhan–Planton soil evaporation term applied over the exposed substrate fraction (25%), re-running the conduction solver for thermodynamic consistency. As summarized in Table 2, activating this dual-pathway coupling produces substantial changes across all three quantification layers.

Table 2: Three-layer quantification results of VWC coupling modules

Module Layer	Matric and Unit	Baseline	VWC-Coupled
L1 Roof Surface	Summer ΔT_roof (°C, mean)	–	−0.970
L1 Roof Surface	Summer ΔT_roof (°C, daytime)	–	−1.812
L1 Roof Surface	Q_roof_lat (W/m², urban)	24.21	50.51 (+26.3)
L2 Canyon Air	Annual ΔT_canyon (°C)	–	−0.205
L2 Canyon Air	Summer ΔT_canyon (°C)	–	−0.256 °C
L3 Building Energy	Annual R_soil (m²-K/W, mean)	0.286	0.324 (+13%)
L3 Building Energy	Annual C_vol (J/m³-K, mean)	1,320,000	2,593,371 (+96.5%)
L3 Building Energy	Decrement Factor f_d (ratio)	0.310	0.175 (−43%)
L3 Building Energy	Phase Lag Δt (min)	268	399 (+131)

At the L1, the latent heat budget increases by 108.6% relative to the fixed-ET baseline. The corresponding canyon-scale air temperature reduction reaches -0.205 °C on an annual basis, with the VWC-specific contribution (-0.084 °C) representing a 5.6-fold amplification com-

pared to the solar-only increment (-0.015 °C). At the L3, the thermal mass error between the HB-static module and the VWC-dynamic module is both the largest and the most directionally consistent, with C_vol being underestimated at every hour of the year.

Figure 6 illustrates both the surface cooling signal and the thermal mass implications of VWC dynamics. The left panel traces the mean summer diurnal roof surface temperature across the full 3-month period. The VWC-UWG V3 profile consistently sits below the fixed-ET baseline, with a peak-hour differential of -2.07 °C at noon driven exclusively by the VPD pathway – a cooling contribution absent from the solar-only configuration. The right panel quantifies the annual dynamic phase lag against the fixed EnergyPlus reference. The HB static value of 268 minutes holds constant across all months, while the dynamic Δt (green band) remains persistently above it with the extra lag (always positive, shaded region) averaging +131 minutes throughout the year. This consistent surplus reflects the approximately doubled C_vol under typical NYC moisture conditions: substrate holding roughly 1,270 kJ/m³-K more thermal energy than the static model assumes shifts the interior temperature peak by 2.2 hours, and the accompanying 77% overestimate of the decrement factor f_d means EnergyPlus simultaneously inflates the amplitude of heat transfer through the roof assembly – errors that neither seasonally cancel nor diminish during summer peak cooling periods.

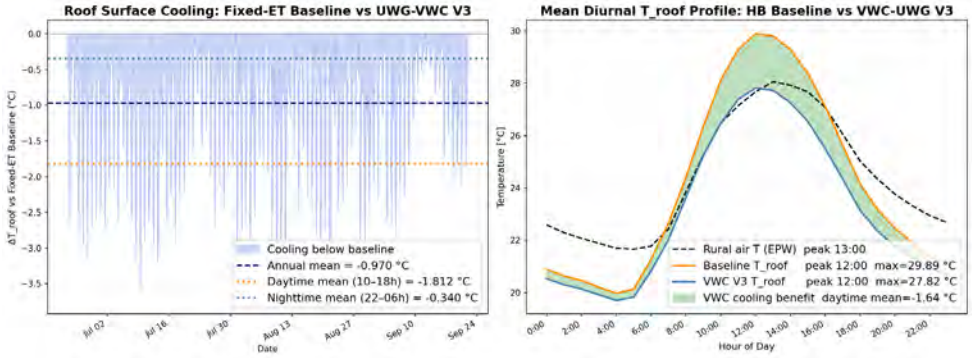

Fig. 6: Summer roof surface temperature and diurnal phase lag of thermal mass

4.4 Parametric Difference Visualization

Figure 7 maps full-greening hygrothermal performance across 287 Manhattan census tracts. Panel A establishes the Landsat-derived UHI baseline, showing a clear gradient from park-dominated zones to dense commercial cores. Panel B spatializes the VWC-UWG V3 roof cooling, with peak reductions concentrated in Lower Manhattan and Midtown; spatial variability exceeds the borough mean, confirming that building density, rather than climate forcing, governs heterogeneity. Panel C extends cooling to canyon scale through the nocturnal VPD-driven component. Panel D integrates thermal stress and cooling capacity into an intervention priority index, highlighting the densest southern tracts as strategic targets.

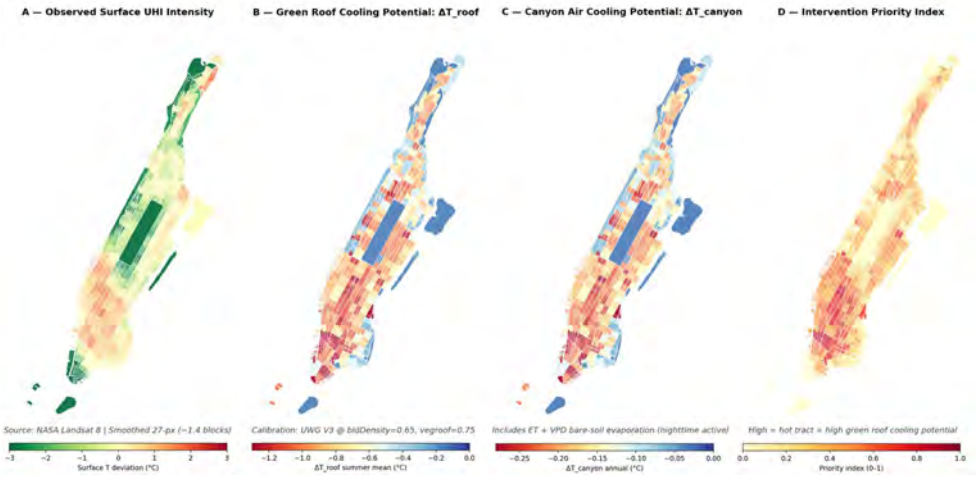

Fig. 7: Manhattan green roof cooling potential and UHI intervention priority

Figure 8 contrasts existing green roof deployment with modeled potential. Current coverage remains negligible relative to full-greening capacity. Overlaying the 72 hottest tracts (Landsat >+0.63 °C) onto this sparse distribution reveals a systematic implementation gap in areas of highest thermal stress. Quadrant analysis confirms a pronounced spatial mismatch: high-density districts simultaneously exhibit the greatest UHI intensity and the strongest modeled roof-cooling capacity (red zone), indicating substantial unrealized mitigation potential.

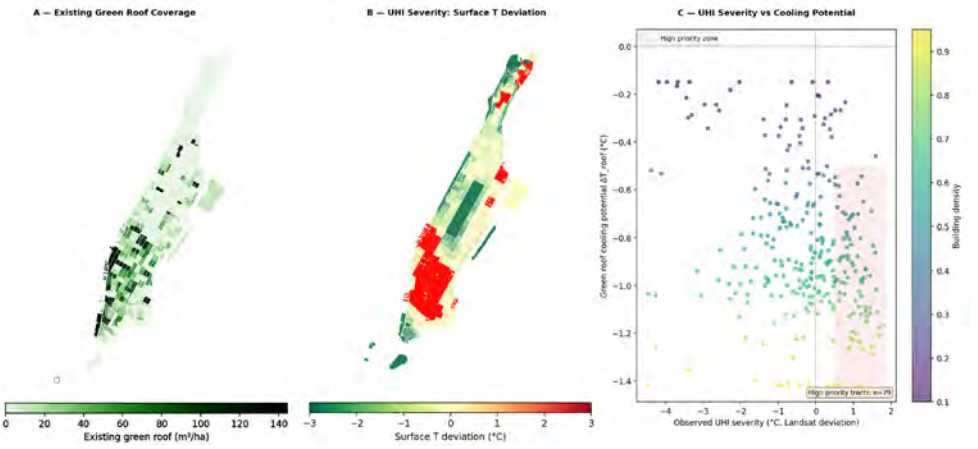

Fig. 8: Existing green roof coverage, UHI hotspots, and spatial potential distribution

In addition, findings show that EnergyPlus thermal-mass errors remain spatially uniform because they depend solely on VWC. However, their absolute impact scales with local UHI intensity, amplifying interior temperature amplitude bias in the hottest Lower Manhattan tracts and reinforcing the importance of moisture-aware substrate modeling.

5 Conclusion and Outlook

This study demonstrates that soil volumetric water content is not a secondary parameter but a primary determinant of green roof hygrothermal performance across three coupled mechanisms. A GRU sequential model captures soil moisture memory that tree-based approaches structurally cannot, yielding an 8760-hour VWC forcing series grounded in monitored green roof dynamics. The VWC-UWG V3 coupling reveals continuous nighttime VPD-driven cooling (-0.34 °C) absent from solar-only models, while the three-layer quantification confirms that EnergyPlus thermal mass assumptions introduce the largest and most persistent bias: volumetric heat capacity is underestimated by 96.5%, producing a 77% overestimate of interior temperature amplitude and a 2.2-hour load-timing error that conventional calibration cannot detect. Applied to Manhattan, parametric scaling shows that green roof cooling potential varies by 1.27 °C across 287 census tracts – a range driven by building density and currently unrealized at less than 2% of modeled capacity.

As urban heat stress intensifies under climate projections, hygrothermal modeling offers a scalable pathway toward performance-based green roof design standards. Future work should extend the dynamic thermal mass correction into EnergyPlus via EMS actuators, validate the sequential model across substrate types and climate zones, and integrate real-time irrigation scheduling to close the gap between modeled potential and operational performance.

Acknowledgements

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Assessment of Pedestrian-Level Wind Environment in Traffic-Oriented Pocket Parks Based on Coupled WRF-ENVI-met Modeling

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Abstract: Environmental problems driven by urbanization threaten public health and urban vitality. Improving urban wind environments helps regulate local climate, disperse air pollutants, and enhance quality. Traffic-oriented pocket parks support daily public activities, yet their wind environments are affected by vehicle emissions and complex airflow. However, studies on pedestrian-level wind environments in pocket parks are limited, and integrated analyses linking environmental performance with human activity are insufficient. This study proposes a downscaling simulation framework coupling the mesoscale Weather Research and Forecasting (WRF) model with the microscale ENVI-met model to simulate pedestrian-level wind environments under a unified meteorological background. Typical traffic-oriented pocket parks in Nanjing were selected as case studies. Wind conditions in winter and summer were evaluated, and simulation results were overlaid with the spatial distribution of crowd concentration to identify three spatial types: core conflict zones, seasonally adaptive zones, and stable low-response zones. Results show that the coupled WRF-ENVI-met approach overcomes limitations of traditional field measurements and enables comparative wind environment assessment across multiple pocket parks. Seasonal differences in wind conditions were observed, and pavilion and corridor structures influenced local airflow. Spatial correspondence was identified between wind environment quality and crowd concentration, though this relationship is affected by multiple factors and requires further validation. This study supports climate-adaptive green space design in high-density urban areas.

Keywords: Transit-oriented pocket parks, wind environment, simulation

1 Introduction

Rapid urbanization has led to a range of environmental problems, including urban heat islands and air pollution, posing serious challenges to public health and urban vitality. As a key natural driving force, the urban wind environment provides a direct and effective means to regulate local climate, disperse pollutants, and improve thermal comfort (REN et al. 2018). In the context of urban development shifting toward quality-oriented renewal of existing spaces, pocket parks – characterized by small size and flexible layouts – have become important components for strengthening public space networks and improving residents' quality of life. Among them, traffic-oriented pocket parks located along major urban roads function as highly accessible nodes of public activity, but their wind environments are simultaneously affected by vehicular emissions and complex airflow associated with urban ventilation corridors. This results in a dual condition of high public use and elevated environmental exposure risk. However, current pocket park design practices largely rely on landscape aesthetics and empirical experience, with limited consideration of microclimate performance. In particular, quantitative studies on pedestrian-level wind environments remain insufficient to support human-centered and climate-adaptive spatial optimization. Consequently, the application of digital simulation techniques for accurate and efficient diagnosis of wind environment quality has become a critical issue for sustainable development in high-density urban areas.

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Within landscape architecture research, studies on wind environments are fewer than in architecture and urban planning, although they span macro-, meso-, and micro-scale analyses. Existing studies have focused primarily on block-scale green spaces (ZHANG et al. 2017), residential areas (HONG & LIN 2014), and street canyons (PENG et al. 2021), with limited attention to urban park green spaces (HOU et al. 2018, SHI et al. 2015). Research on pedestrian-level wind environments has mainly examined streets (CHEN et al. 2023), open roads (ABHIJITH et al. 2017), and residential areas (ZHEN et al. 2019), emphasizing the effects of vegetation structure and green space layout (STOJANOVIC et al. 2020, ZHANG et al. 2025). In recent years, research emphasis has shifted from vegetation and green space form toward microclimate regulation related to human health and thermal comfort, promoting the widespread use of the ENVI-met model (HAMI et al. 2019, LIN et al. 2023). Nevertheless, most studies assess wind environments under isolated conditions and rarely integrate spatial use patterns, limiting their ability to characterize site-specific wind quality or support practical design decisions.

Although ENVI-met has advantages in simulating vegetation-related microclimates, its application is constrained by computational demands and limited coverage, making it difficult to support systematic analysis of multiple small urban green spaces. Moreover, its reliance on station-based observations or short-term field measurements as boundary conditions often fails to represent realistic inflow wind fields under complex urban morphology, reducing the reliability of cross-site comparisons. To address these limitations, this study develops a multi-scale downscaling framework that couples the Weather Research and Forecasting (WRF) and ENVI-met models. City-scale meteorological conditions are simulated using WRF to establish a unified atmospheric background, which is then used as dynamically stable boundary conditions for ENVI-met. This approach enables simulation of pedestrian-level wind fields in multiple pocket parks under consistent meteorological conditions and supports the identification of site-specific wind patterns and potential risk areas relevant to planning and design.

Based on multi-dimensional assessment at the urban scale, this study selects representative traffic-oriented pocket parks as empirical cases and develops a framework that integrates refined wind simulation, evaluation of pedestrian-level (1.5 m) wind environment, and overlay analysis with spatial use patterns. A coupled simulation approach is adopted to link WRF at the urban scale with ENVI-met at the site scale, and the results are validated using field measurements. Wind environment characteristics and seasonal quality are evaluated for both summer and winter, and their spatial correspondence with patterns of park use is examined. The study aims to: (1) develop and validate a WRF-ENVI-met downscaling framework for fine-scale simulation of pedestrian-level wind environments; (2) establish wind environment evaluation criteria and identify seasonal problem areas; and (3) explore the relationship between wind environment quality and spatial use to inform the optimization of traffic-oriented pocket parks. Ultimately, the goal is to improve environmental quality, promote public health, and enhance spatial vitality in high-density historic urban areas.

2 Method

2.1 Study Object

This study focuses on traffic-oriented pocket parks along urban roads in the old city of Nanjing. Traffic-oriented pocket parks are a clearly defined functional category in the Nanjing

Pocket Park Construction Guidelines (Trial). They are small open green spaces, usually less than 1 hectare, developed in underutilized areas near transportation facilities such as bus stops, roads, intersections, and underpasses. These parks primarily serve pedestrians for transit gathering, short-term stops, and leisure activities.

2.2 Selection of Typical Meteorological Days

To reduce the influence of incidental weather, this study selected "typical days" in winter and summer as the reference for meteorological simulations. Based on nearly 20 years of wind speed and direction data from the Nanjing station of the U.S. National Oceanic and Atmospheric Administration (NOAA), the average wind speed and prevailing wind direction for each season were calculated. Actual dates with the smallest deviations from the seasonal averages were then chosen as the typical days. The final selected dates were June 24, 2023, for summer (average wind speed 2.826 m/s, prevailing wind direction 110°) and February 23, 2023, for winter (average wind speed 2.368 m/s, prevailing wind direction 90°).

2.3 Mesoscale Wind Environment Simulation

This study employed the WRF version 4.5.0, incorporating the fifth-generation reanalysis product (ERA5) data, static geographical datasets, and local climate zone (LCZ) data. A four-level nested domain approach was used to simulate the wind, thermal, and humidity environment on typical summer and winter days within the study area. Detailed model configuration parameters are listed in Table 3. The WRF simulation results were validated against hourly observations from the Nanjing National Meteorological Station provided by the China Meteorological Data Service Centre. Validation metrics included bias, root mean square error (RMSE), and correlation coefficient (R).

Table 1: Summary of WRF model configuration.

	D01	**D02**	**D03**	**D04**
Horizontal resolution	9 km	3 km	1 km	333.33m
Microphysics	WRF Single-Moment 5-class scheme			
Cumulus scheme	Kain-Fritsch (new Eta) scheme			
Land surface scheme	Noah Land Surface Model			
Surface layer scheme	Revised MM5 Monin-Obukhov scheme			
Planetary boundary layer scheme	Yonsei University scheme			
Longwave radiation scheme	RRTMG scheme			
Shortwave radiation scheme	RRTMG scheme			
Surface urban physics scheme	BEP scheme			

2.4 Selection of Representative Traffic-Oriented Pocket Parks

This study applied a three-stage screening approach based on wind environment, air pollution, and traffic location to identify representative traffic-oriented pocket parks. First, poorly ventilated areas were identified based on the spatial distribution of average wind speed on the typical summer meteorological day simulated by WRF for the old city of Nanjing, with a focus on zones characterized by the lowest wind speed levels. Second, areas with high air

pollution were delineated within the influence ranges of air quality monitoring stations in the old city of Nanjing that recorded the highest ten-year average PM2.5 concentrations during winter. Third, among candidate green spaces meeting the criteria of low wind speed and high pollution, sites adjacent to high-grade roads and located close to schools were prioritized to facilitate long-term field investigation. Based on this screening process, the green space along Beijing East Road and Heping Park in Nanjing were ultimately selected as the study sites.

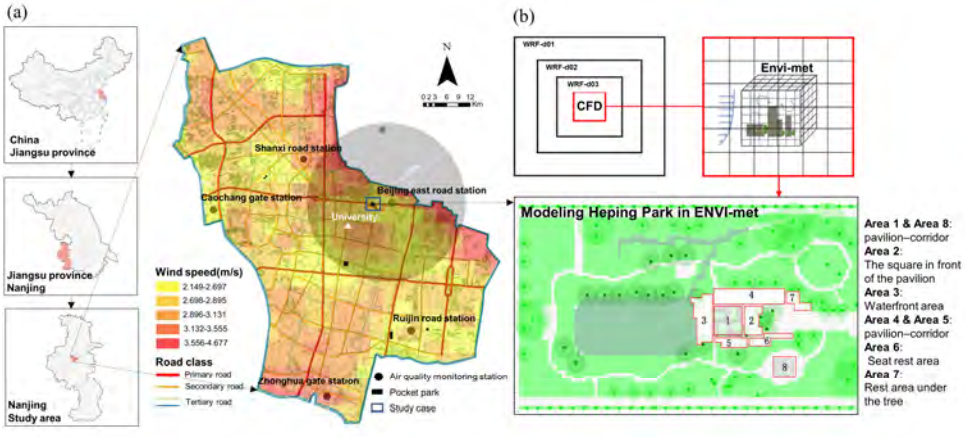

Fig. 1: (a) Study area and sample selection, (b) Schematic diagram illustrating the principle of WRF-ENVI-met wind environment simulation

2.5 Coupled WRF-NVI-met Downscaling Simulation

This study develops a coupled downscaling framework to simulate pedestrian-level wind environments in urban pocket parks under a unified atmospheric background and to reduce uncertainty associated with limited on-site data and scale mismatch in conventional meteorological forcing. The proposed workflow couples WRF and ENVI-met models. Based on the location of Heping Park, hourly meteorological variables were extracted from the corresponding WRF grid cells, including 10 m wind speed, 2 m air temperature, and 2 m relative humidity. These data were then used as boundary conditions to generate a high-resolution and dynamically stable initial meteorological field in ENVI-met using the Full Forcing mode. The pedestrian-level wind environment within the pocket parks was simulated at a height of 1.5 m through the coordinated operation of multiple ENVI-met modules. Within the ENVI-met domain, a horizontal resolution of 1 m × 1 m was adopted to accurately represent landscape elements such as water bodies, vegetation, and pavilion-corridor structures. To verify the reliability of the proposed approach, simulated wind speeds were validated against field measurements collected at boundary monitoring points of Heping Park.

2.6 Data Collection of Crowd Concentration Intensity

Crowd concentration intensity was used to represent spatial use within pocket parks and was quantified as the hourly number of people staying in each activity space. Visitor spatiotem-

poral behavior was captured using a combination of Wi-Fi probe sensing and on-site observation to characterize within-park crowd distribution. Field surveys were conducted during peak periods on one day in both summer and winter (08:00-11:00 and 14:00-17:00). Three Wi-Fi probes were deployed in each park, each with an approximate 40 m coverage radius. Mobile device signals were recorded at 30-minute intervals, including MAC addresses, received signal strength, and timestamps. Visitor locations were estimated using triangulation, achieving meter-level accuracy. To compensate for the undercounting of individuals without mobile phones (e. g., children and older adults), panoramic cameras were used to record on-site scenes, and image recognition identified and counted visitors, ensuring completeness.

3 Results and Discussion

3.1 Validation of Wind Environment Simulation Data

Using the summer period as an example, WRF outputs were validated against meteorological station observations. The model slightly overestimated wind speed (Bias = +0.93 m/s; RMSE = 1.62 m/s; R = 0.66) and air temperature (Bias = +1.50 °C; RMSE = 1.93 °C; R = 0.96), while relative humidity was underestimated (Bias = −16.19%; RMSE = 18.52%; R = 0.91). WRF-simulated wind, temperature, and humidity for the Heping Park grid cell were then used to drive ENVI-met for pedestrian-level wind environment simulation. ENVI-met wind speeds showed a small positive bias (Bias = +0.21 m/s; RMSE = 0.24 m/s; R = 0.77) when validated against in-park measurements. Overall, errors were within acceptable ranges, supporting the feasibility of the coupled framework.

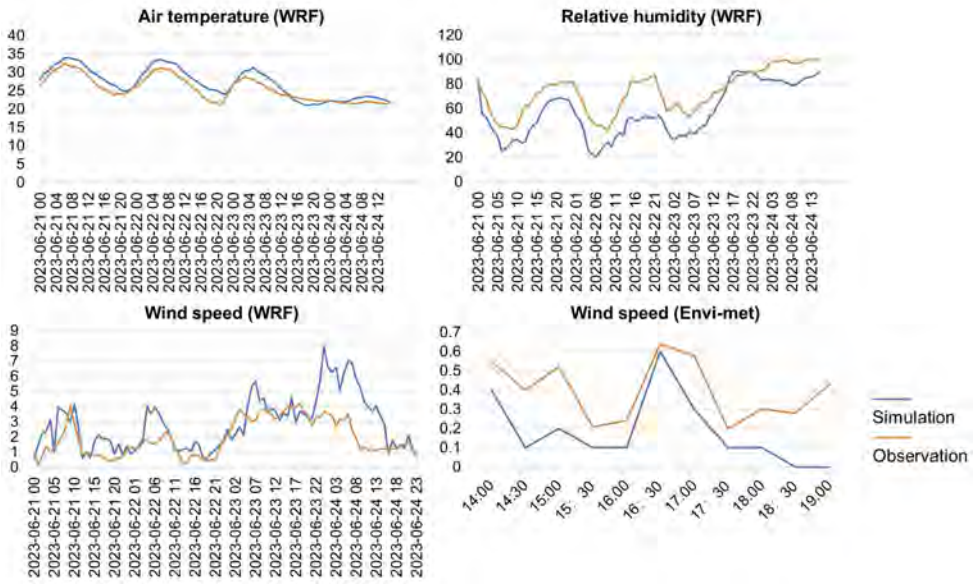

Fig. 2: Comparison between simulated and observed values

3.2 Wind Environment Evaluation Criteria

A wind speed evaluation framework for the pedestrian-level wind environment was established based on the Green Building Evaluation Standard (GB/T 50378-2019), the Shenzhen Green Building Evaluation Specification (SZJG30-2009), and the Hong Kong Planning Department's Air Ventilation Assessment Technical Guidelines. The framework includes two components: (1) wind-induced comfort and safety thresholds and (2) ventilation performance. Wind speeds below 1.0 m/s were classified as calm wind, which may contribute to thermal discomfort and pollutant accumulation, whereas wind speeds above 5.0 m/s were considered to involve potential pedestrian safety risks. Ventilation performance was assessed using a wind speed amplification factor ≥ 0.3, following SZJG30-2009. Using seasonal background wind speeds, the corresponding lower limits were 0.975 m/s in summer and 0.525 m/s in winter. The detailed criteria are provided in Table 2.

Table 2: Pedestrian-level wind speed zoning evaluation

Primary Category	Secondary Zone	Wind Speed Range (m/s)	Wind Environment Characteristics
Calm-wind Zone	Extremely Calm-wind Zone	Summer: < 0.975 Winter: < 0.525	Summer: Insufficient ventilation for convective cooling; Winter: Stagnant air; poor pollutant dispersion
Calm-wind Zone	Moderately Calm-wind Zone	Summer: 0.975-1.0 Winter: 0.525-1.0	Summer: Meets minimum ventilation, but below comfort range; Winter: Insufficient for comfort and pollutant dispersion
Suitable Wind Speed Zone	–	Summer/Winter: 1.0-5.0	Moderate wind speed balances comfort and pollutant dispersion
High Wind Speed Zone	–	Summer/Winter: > 5.0	Wind speed is too high, posing potential safety hazards

3.3 Results of Wind Environment Evaluation

(1) Seasonal Wind Environment Evaluation Results

In summer, suitable wind speeds (1.0-5.0 m/s) dominated the park (97.66%), with no high wind speed zones (> 5.0 m/s). Extremely calm (< 0.975 m/s) and sub-calm (0.975-1.0 m/s) areas accounted for 1.92% and 0.42%, respectively. Wind speeds in the central pavilion-corridor, and roadside pavilions, major resting spaces, were below 1.0 m/s, highlighting areas for wind environment optimization. In winter, calm wind areas increased to 67.85%, including 2.73% extremely calm, which hinders pollutant dispersion, such as PM2.5. Suitable wind speeds (1.0-5.0 m/s) accounted for 32.15%, mainly over water surfaces and scattered green spaces, with no high wind speed zones. Within the suitable range, usable activity areas were limited and concentrated over water, indicating suboptimal winter wind environments for accessible spaces.

(2) Spatial Correspondence Between Wind Environment and Crowd Concentration

Overlaying wind environment maps with crowd concentration revealed consistent spatial differentiation across seasons. In summer, the waterfront activity area (Area 3) benefited from an open water surface to the east and its location in a wind acceleration zone, showing the

best ventilation and relatively high activity. The area north of the central pavilion-corridor (Area 4) was sheltered by vegetation, with stable airflow and moderate activity. In contrast, the southern and southeastern areas (Areas 5 and 6) were in wind shadow zones, with reduced wind speeds and sparse activity. Notably, the central pavilion-corridor (Area 1) had the highest crowd concentration (up to 74 people) but low wind speeds. In winter, key functional areas showed a stronger mismatch. Area 1 remained the most used space but had the lowest wind speeds, dropping below 0.5 m/s under the structure, forming a "high crowd density-low wind speed" conflict. Area 3 had higher wind speeds near open water but attracted fewer visitors. Area 4, in wind speed increase zones, showed higher wind speeds and activity. In contrast, Area 5 remained in a wind shadow zone, with poor ventilation and low activity.

Table 3: Number of people and activity types by area, across seasons

Area ID	Activity types	Total count (Winter)	Total count (Summer)
Area 1	Resting, board games	55	74
Area 2	Dancing, fitness activities	13	15
Area 3	Resting	6	21
Area 4	Fitness activities, board games	35	41
Area 5	Resting, board games	5	4
Area 6	Resting	10	6
Area 7	Resting	16	16
Area 8	Resting	12	18

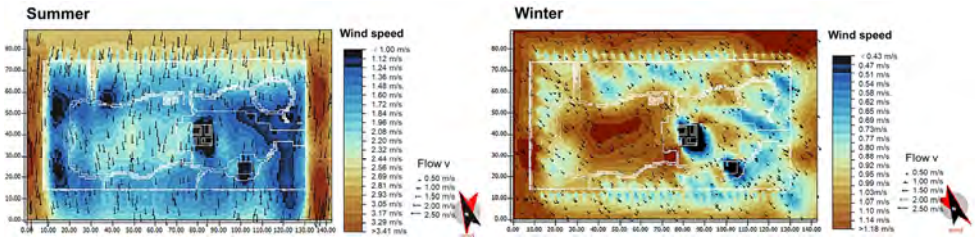

Fig. 3: Spatial distribution of wind speed on typical weather days in different seasons

3.4 Discussion

(1) Seasonal Differences and Landscape Effects on Wind Environment

The results show a seasonal contrast: ventilation is favourable in summer, while winter is dominated by calm conditions, implying weaker dilution of traffic-related pollutants. This gap is amplified by built elements. Compared to vegetation, pavilion-corridor structures exert stronger wind-blocking effects, creating persistent low-speed zones and reorganizing airflow into wind shadow and acceleration zones. These effects explain why the same functional space can remain under-ventilated across seasons, even with different background winds. For traffic-oriented pocket parks, pavilion-corridor design should be a primary control variable for wind environments. Early-stage seasonal simulations can test the placement, orientation, and opening strategy of such structures to avoid creating under-ventilated resting spaces.

(2) Classification of Wind-Crowd Spatial Relationships

Overlaying wind environment results with crowd concentration spatial data reveals a spatial correspondence, classified into three types. Core conflict zones are characterized by persistent low wind speed and high crowd concentration in both summer and winter, as seen in Area 1. Seasonally adaptive zones show a favourable match between suitable wind conditions and high activity in summer (Areas 3 and 4), while in winter, Areas 4 and 7 serve as main comfortable activity spaces, and Area 3 experiences a marked decline in crowd presence under higher wind speeds. Stable low-response zones, represented by Areas 5 and 6, consistently exhibit low wind speed and low crowd concentration across seasons. Crowd concentration intensity is influenced by multiple factors, including landscape, thermal conditions, and individual preferences. The classification aims to describe the spatial co-occurrence of wind environment quality and activity intensity to support design diagnosis and prioritization, rather than establishing a one-to-one causal relationship. Any causal link between wind environment quality and crowd concentration requires further quantitative testing. Incorporating crowd vitality into wind environment evaluation, this study aims to guide localized wind optimization to enhance pollutant dispersion and better serve park users.

(3) Implications for Pocket Park Planning and Renovation

Based on the above findings, implications for the planning and renovation of pocket parks can be identified. Multi-season wind environment simulations should be conducted prior to construction to avoid seasonal imbalances in spatial use caused by conflicting summer and winter wind conditions, which may lead to inefficient use of public resources. In the renewal of existing parks, pedestrian flow monitoring can be combined with adjustments to landscape nodes and pathways to guide activities toward areas with more favorable wind conditions, while prioritizing microclimate improvement in areas with consistently high crowd concentration. Vegetation configuration should be adapted to seasonal wind characteristics through an appropriate combination of evergreen and deciduous species, providing wind protection while maintaining ventilation and avoiding the formation of calm wind zones.

(4) Methodological Innovation and Potential for Extension

The key methodological contribution is a reusable workflow that supports consistent cross-park comparison of pedestrian-level wind environments under a unified atmospheric background. By reducing reliance on extensive field measurements, it offers a time- and cost-efficient approach for multi-site assessments and enables synchronized evaluation across parks. Beyond wind environments, the workflow can be extended to simulate air temperature and humidity, thereby supporting thermal comfort assessment. As a digital workflow applicable at the design stage, it can inform microclimate-oriented decisions on node placement and landscape element configuration, offering practical value for climate-adaptive green space planning in high-density urban areas.

4 Conclusion and Outlook

This study focuses on traffic-oriented pocket parks, selecting representative cases through a multi-dimensional evaluation. A coupled WRF-ENVI-met simulation workflow was developed to model pedestrian-level wind environments, along with corresponding evaluation criteria. Based on simulation results, wind environment quality was overlaid with crowd spatial

use patterns, identifying three typical spatial relationships. Due to limitations in experimental conditions and model accuracy, there are certain errors in crowd behavior tracking data and simulation models. Additionally, the current overlay classification primarily describes spatial co-occurrence patterns rather than causal relationships. Future research will further simulate the impact of landscape element characteristics on microclimate formation and conduct comparative studies across multiple scenarios, aiming to develop human-centered microclimate regulation strategies and health-oriented design approaches for pocket parks.

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Threshold-Driven Optimization of Elderly Summer Thermal Comfort in Waterfront Green Spaces: Evidence from the Qinhuai River

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Abstract: Older adults are increasingly constrained by summer heat in China's hot-summer and cold-winter cities, yet the renewal of waterfront green spaces often lacks elderly-specific thermal comfort targets that can guide design decisions. This study derives an elderly summer comfort threshold using Physiological Equivalent Temperature (PET) from field measurements and on-site questionnaires across three Qinhuai River waterfront sites in Nanjing, and then applies the threshold in ENVI-met scenario simulations to compare alternative configurations of key landscape elements. The results indicate that the elderly comfort range is lower and narrower than values commonly reported for the general adult population, suggesting a reduced tolerance to heat stress in waterfront outdoor settings. Scenario comparisons further show that vegetation related parameters exert the largest influence on the area meeting the comfort threshold, while surface reflectance and shaded facilities provide additional but comparatively limited gains. By linking a field-derived, context-specific threshold to simulation-based configuration testing, the study provides an operational workflow to support age-friendly and climate-responsive waterfront renewal in hot-summer and cold-winter cities.

Keywords: Outdoor thermal environment, elderly, Physiological Equivalent Temperature (PET), simulation in Envi-met, urban waterfront green space

1 Introduction

As China's urban population ages at an accelerating pace, older adults have become a major user group of urban open spaces (TINSLEY et al. 2002). In Nanjing, located in the hot-summer and cold-winter zone (XU et al. 2019), summertime heat markedly suppresses older adults' daytime activities (BRANDON et al. 2009) and heightens health risks associated with heat exposure (HUGHES & NATARAJAN 2019). Waterfront green spaces can provide ventilation corridors, blue-green connectivity, and accessible daily destinations; however, renewal and design practices often prioritize landscape aesthetics and mass recreation while paying insufficient attention to elderly-specific thermal comfort thresholds and to how controllable landscape elements shape thermal perception.

Research related to thermal comfort can be traced back to the field of building science for indoor environments. ASHRAE-55 outlined thermal comfort as 'that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation' (RUPP et al. 2015). As research progressed, thermal comfort was gradually extended to the outdoor field (NIKOLOPOULOU et al. 2001), with a particular focus on urban public spaces (TALEGHANI et al. 2015). Several studies have confirmed the positive impact of green spaces on thermal comfort by investigating urban green spaces. Waterfront green spaces, as unique urban areas combining water and vegetation, play a critical role in regulating urban ecological health and mitigating climate issues (FAN et al. 2022). Studies have shown that the reasonable combination of water and green space can effectively improve the local microclimate

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(XU et al. 2024). However, compared with outdoor thermal-comfort studies on the general population (ZHANG et al. 2024), existing research focusing on older adults – a vulnerable group with higher heat risk and weaker thermoregulatory capacity – remains limited, particularly in terms of characterizing comfort thresholds and developing spatial intervention strategies. Therefore, this study examines waterfront green spaces in the hot-summer and cold-winter region, identifies elderly-specific thermal-comfort thresholds, and develops threshold-driven spatial optimization strategies to inform age-friendly, climate-adaptive waterfront renewal.

This study investigates representative waterfront green spaces along the Qinhuai River. Field measurements were paired with on-site questionnaires to collect hourly microclimatic variables on three typical summer days and to record older adults' thermal sensation and comfort votes. Physiological Equivalent Temperature (PET) was calculated using the RayMan model and regressed against Thermal Sensation Votes (TSV) to derive an elderly summer comfort threshold under waterfront conditions. The threshold was then embedded into ENVI-met simulations to evaluate the spatial distribution of PET under alternative, design-controllable configurations of key landscape elements and to translate simulation outputs into a threshold-based performance metric, thereby proposing threshold-driven optimization strategies for waterfront landscapes. The objectives are as follows: 1) delineate the elderly PET comfort interval for summer waterfront green spaces; 2) identify key landscape elements that influence elderly thermal comfort and explain their mechanisms; 3) propose threshold-constrained, design-operable configuration recommendations for age-friendly waterfront renewal.

2 Methodology

2.1 Study Region and Data Sources

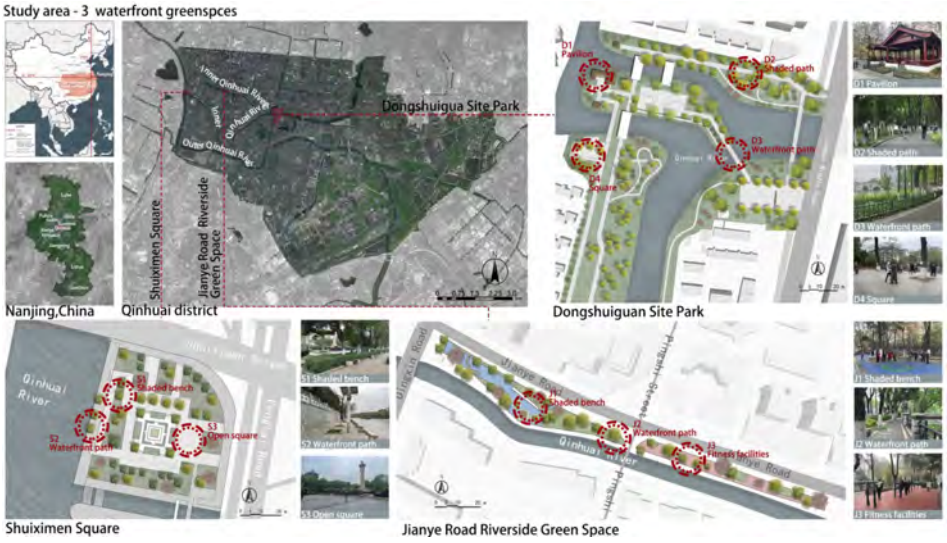


Fig. 1: Location of the three Qinhuai River waterfront study sites

Three waterfront sites – Dongshuiguan Park, Shuiximen Square, and the Jianye Road Riverside Green Space – were selected as areas frequently used by older adults yet exhibiting poor summer thermal comfort. Figure 1 shows the location of the three sites and the layout of the measurement points. Ten measurement points were deployed across common activity settings and contrasting micro-environments (e. g., sun-exposed promenades, tree-shaded areas, and near-water edges) to capture the influence of existing landscape elements on the local thermal environment. On three typical clear, hot summer days (08:00-19:00), synchronized hourly observations and short on-site questionnaire surveys were conducted. Microclimatic monitoring included air temperature, relative humidity, wind speed and solar radiation, with all probes mounted at 1.5 m (the breathing zone) to ensure consistent exposure and placed to avoid temporary obstructions. The questionnaire documented basic demographic information and activity status and, under steady activity, a 7-point Thermal Sensation Vote (TSV) and a 4-point Thermal Comfort Vote (TCV). In total, 350 questionnaires were distributed, and 335 valid responses were collected.

2.2 Thermal Index Selection and PET Calculation

Considering that a single meteorological variable cannot fully characterize outdoor thermal load, this study adopted PET (Physiological Equivalent Temperature) as a comprehensive thermal index. PET is based on Hoppe's MEMI model. It is defined as the indoor air temperature at which the core and skin temperatures of a reference person are identical to those under a given outdoor environment. During older adults' PET calculaion, clothing insulation was calculated from ASHRAE component clo values combined with observed attire, yielding a summer mean of 0.53 clo; metabolic rate was determined with reference to ISO 7730 and field activity types, yielding a summer mean of 149 W/m². Hourly meteorological data, together with clothing and metabolic parameters, were input into RayMan to compute PET at each measurement point, providing the basis for threshold inference and factor-association analyses.

2.3 Data Analysis

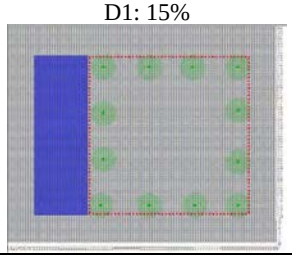
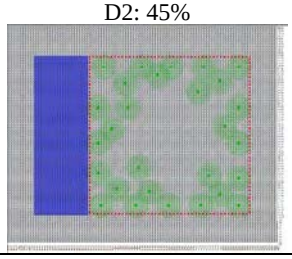
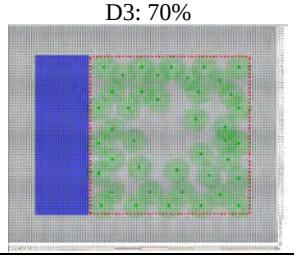
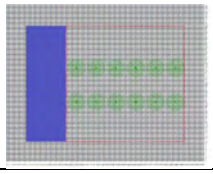
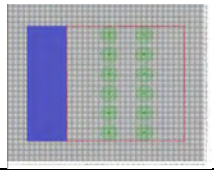
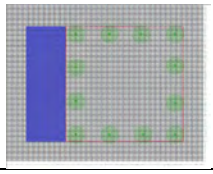
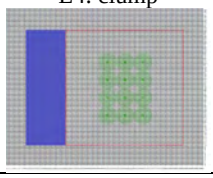
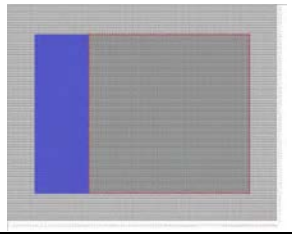
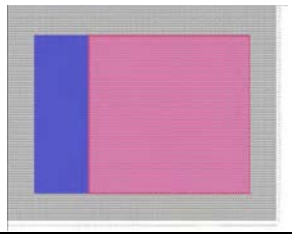
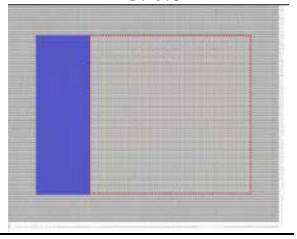
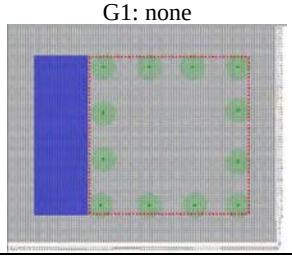
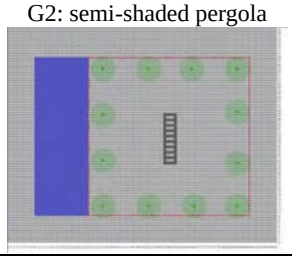
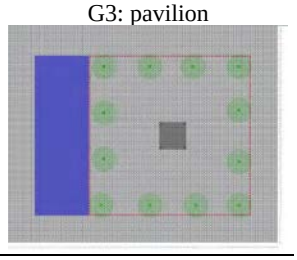
IBM SPSS was used to process the questionnaire and PET data. First, Pearson correlation and quadratic polynomial regression were employed to fit the TSV-TCV relationship, identifying the correspondence between thermal sensation and comfort as well as the point of maximum comfort. Subsequently, with PET as the independent variable and TSV as the dependent variable, weighted linear regression with 0.5 °C binning was performed to infer the summertime neutral temperature and the comfort-threshold interval for older adults. Landscape attributes at each measurement point were then extracted to construct a PET-factor Pearson correlation matrix, on the basis of which key variables were screened and used to specify inputs for numerical simulations.

2.4 Simulation Model and Scenarios

This study used ENVI-met to analyze the impact of different different landscape configurations on thermal comfort. ENVI-met, grounded in the principles of thermodynamics and hydrodynamics, dynamically simulates interactions between building facades, vegetation, and air, allowing for the visualization of outdoor thermal environments. As a result, it has been extensively applied in urban design (ABD ELRAOUF et al. 2022) and other related fields.

To examine the applicability and response magnitude of the threshold under different landscape configurations, a typical waterfront unit was established in ENVI-met: the river width was simplified to 10 m, and the waterfront green unit to 30 m × 30 m (consistent with the observed average width of the Qinhuai River, 9.8 m, and the common 10-50 m waterfront green space). Numerical grid parameters were set to x = 100, y = 80, z = 20, with horizontal spacing dx = dy = 0.5 m, vertical layer thickness dz = 1 m, and five-fold refinement in the near-ground layer. The simulation period covered 00:00-18:00 on a typical summer day, with 08:00 as the principal comparison time. Based on correlation diagnostics and site characteristics, four key variables were selected for single-factor scenarios: tree-canopy coverage (15%/45%/70%), planting pattern (row/column/enclosure/clump), pavement albedo (0.3/0.5/0.8), and landscape structure (none/semi-shaded pergola/fully shaded pavilion). These variables and level ranges were abstracted from recurring, design-controllable elements observed across the three Qinhuai River sites and from feasible retrofit options for riverfront rest nodes, allowing simulation outcomes to be interpreted back to the case sites.

Table 1: Simulation scenarios

Tree-canopy coverage	D1: 15%	D2: 45%	D3: 70%	
				
Planting pattern	E1: row	E2: column	E3: enclosure	E4: clump
				
Pavement albedo	F1: 0.3	F2: 0.5	F3: 0.8	
				
Landscape structure	G1: none	G2: semi-shaded pergola	G3: pavilion	
				

3 Results

3.1 Elderly TSV-TCV Characteristics and Threshold Determination

The survey shows that, in summer, TSV among older adults are dominated by "slightly warm" (57.6%) and "warm" (26.5%), with "neutral" accounting for 14.1% and "very hot" for 1.8%. TCV indicate a high prevalence of discomfort (83.5%, including 51.2% slightly uncomfortable and 30.6% uncomfortable), while the proportions for comfortable and extremely uncomfortable are 16.5% and 1.8%, respectively. Pearson correlation and quadratic regression reveal a significant positive relationship between TSV and TCV ($r = 0.684$, $p < 0.01$), with a good quadratic fit ($R^2 = 0.683$); the comfort optimum corresponds to TSV = −0.625 (slightly cool). Considering the field distribution, TSV = 0 is adopted as the target sensation for sustainable use of existing waterfront green spaces. The quadratic relation is given in Eq. (1):

$$TCV = 0.16\,TSV^2 + 0.2TSV + 0.746 \tag{1}$$

Further, binned weighted linear regression shows a significant linear relationship between TSV and PET ($R^2 = 0.82$), as in Eq. (2):

$$TSV = 0.14PET - 3.12 \tag{2}$$

From the TSV-TCV model above, the summertime comfort threshold for older adults is TSV $\in$ [0, 0.78). According to the linear TSV-PET relation, the PET comfort range for older adults in waterfront green spaces during summer is [22.29 °C, 27.85 °C), with an interval width of 5.56 °C.

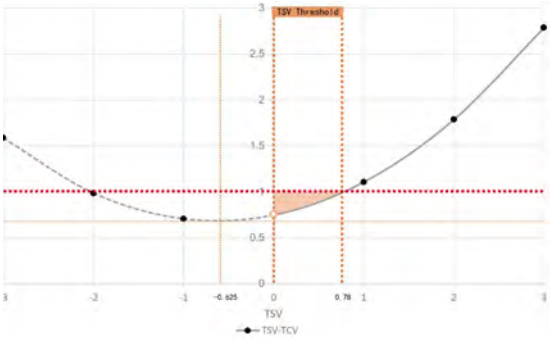


Fig. 2:
Correlation between TSV and TCV

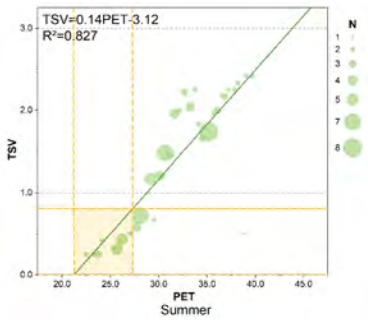


Fig. 3:
Threshold of elderly summer thermal comfort

3.2 Correlation Between Landscape Characteristics and Elderly Thermal Comfort

At the overall level, PET is significantly correlated with landscape factors, with influence ranked as: tree-canopy coverage > planting pattern > plant community structure > landscape-structure type > pavement albedo. Because multiple factors co-act at field points, ENVI-met single-factor scenarios are further employed to isolate independent effects.

Table 2: Basic prototype and related parameters

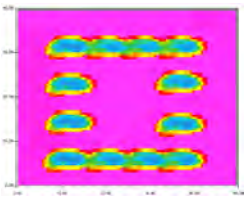
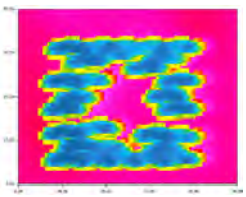
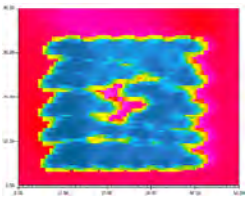
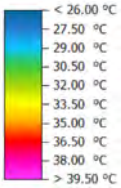
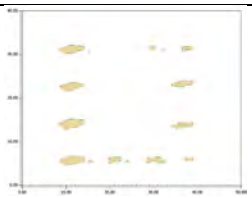
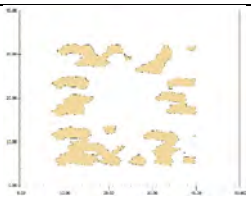
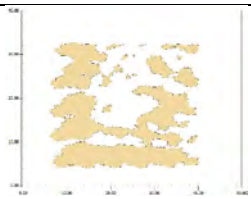
Variables	Off-shore distance	Plant commu-nity struc-ture	Tree-canopy coverage	Plant-ing pat-tern	Shrub enclo-sure	Shrub height	Pave-ment albedo	Land-scape-structure type
Pearson correlation coefficients	0.178 0.066	-0.367 0.000	-0.499 0.000	-0.415 0.000	-0.291 0.012	-0.25 0.010	0.298 0.000	-0.347 0.000

3.3 Thermal-Comfort Simulation Results

(1) Association between Tree-Canopy Coverage and Thermal Comfort

When tree-canopy coverage increases from 15% to 45% and 70%, the site-wide mean PET decreases continuously, and the proportion of area falling within the elderly PET comfort threshold rises from 3.15% to 15.18% and 26.20%. Within the 15%-70% range, each 10% increase in coverage raises the comfort-area ratio by approximately 4.19 percentage points, yielding a monotonic, near-linear relationship that confirms the primacy of shade in expanding "comfort patches."

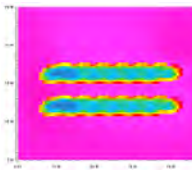
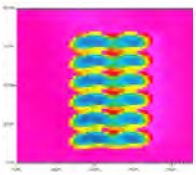
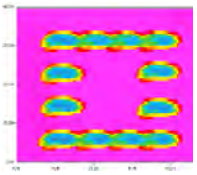
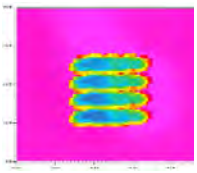
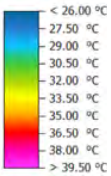
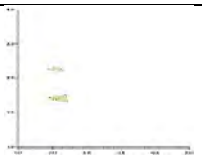
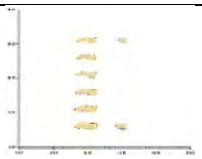
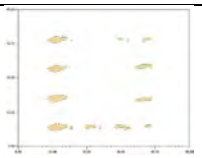
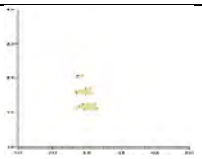
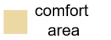
Table 3: PET distribution at 1.5 m and 08:00 in summer under different canopy coverages

	D1: 15%	D2: 45%	D3: 70%	legend
PET				
	Min: 27.00 °C Max: 41.21 °C	Min: 26.34 °C Max: 39.93 °C	Min: 25.91 °C Max: 39.49 °C	
RATIO				
	3.15 %	15.18 %	26.20 %	

(2) Association between Planting Pattern of Trees and Thermal Comfort

At the same canopy coverage (15%), planting patterns differ markedly: mean PET follows row > clump > enclosure ≈ column (column/enclosure ≈ 38.4 °C). The within-threshold area ratio is highest for the column pattern (3.25%) and lowest for the row pattern (0.69%), indicating that aligning with the prevailing wind to form a coordinated "shade + ventilation" corridor effectively reduces peak PET and enlarges comfort space.

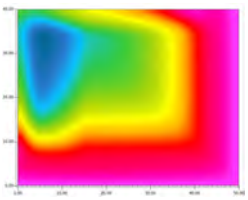
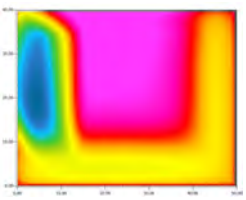
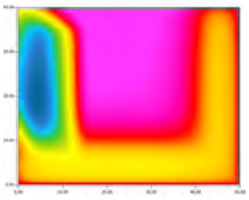
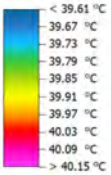
Table 4: PET distribution at 1.5 m and 08:00 in summer for different planting patterns

	E1: row	E2: column	E3: enclosure	E4: clump	legend
PET					
	Min: 27.48 °C Max: 40.69 °C Ave: 39.02 °C	Min: 27.01 °C Max: 40.42 °C Ave: 38.40 °C	Min: 27.00 °C Max: 41.21 °C Ave: 38.49 °C	Min: 27.48 °C Max: 41.18 °C Ave: 38.83 °C	
RATIO					
	0.69%	3.25%	3.15%	1.12%	

(3) Association between Surface Albedo and Thermal Comfort

Increasing surface albedo from 0.3 to 0.5 and 0.8 reduces mean PET by 0.8-1.3 °C. Although this effect alone is insufficient to push PET into the comfort band, it provides a positive basal improvement and should be used synergistically with vegetative shade. Under hot conditions, light-colored, high-albedo materials can effectively improve local thermal comfort.

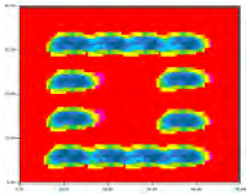
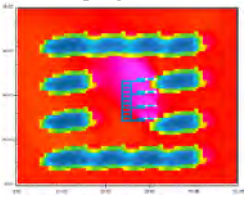
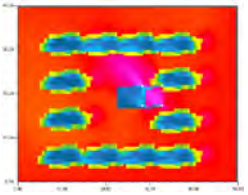
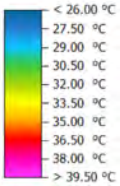
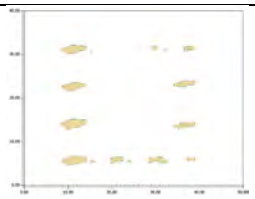
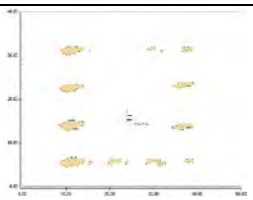
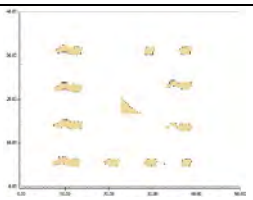
Table 5: PET distribution at 1.5 m and 08:00 in summer for different pavements

	F1: dark granite, 0.3	F2: concrete, 0.5	F3: light granite, 0.8	legend
PET				
	Min: 40.33 °C Max: 40.98 °C Ave: 40.70 °C	Min: 39.61 °C Max: 40.21 °C Ave: 39.98 °C	Min: 38.31 °C Max: 38.87 °C Ave: 38.67 °C	

(4) Association between Landscape Structures and Thermal Comfort

In terms of structures, average PET follows “none > semi-shaded pergola > fully shaded pavilion.” Relative to no structure, a fully shaded pavilion reduces mean PET by 1.17 °C and increases the comfort-area by 1.51%, forming a stable central “cool core” that serves as a reliable daytime refuge for older adults; pergolas are effective as transitional edges, but their overall cooling magnitude is limited.

Table 6: PET distribution at 1.5 m and 08:00 in summer for different landscape structures

	G1: none	G2: semi-shaded pergola	G3: fully shaded pavilion	legend
PET				
	Min: 27.0 °C Max: 41.21 °C Ave: 38.49 °C	Min: 26.99 °C Max: 44.16 °C Ave: 38.40 °C	Min: 26.91 °C Max: 44.32 °C Ave: 36.32 °C	
RATIO				
	3.15%	3.46%	4.66%	

4 Discussion

To clarify the nexus between the case sites, the questionnaire, and the simulation experiment, this discussion explicitly connects the analyses. The Qinhuai River sites provide the real microclimate contexts in which older adults' thermal sensation and comfort were recorded, enabling the derivation of a context-specific PET comfort threshold. The ENVI-met experiment then uses the same threshold to evaluate design-controllable element configurations within a typical waterfront unit abstracted from the case sites, translating scenario outputs into a comparable performance metric (the area meeting the elderly PET range). This linkage explains how the context-specific optimization contributes to the overall workflow, from evidence to design decisions.

4.1 Group and Regional Differences of Elderly Thermal-Comfort Thresholds

Based on the regression model, the neutral PET (NPET) for older adults in summer is 22.29 °C, and the PET comfort threshold is 22.29-27.85 °C. In comparable studies of waterfront green spaces, research conducted in humid-hot regions reported a neutral PET of 26.80 °C for adults aged 25-44 years (LUO et al. 2024). In contrast, the waterfront space in Nanxun Ancient Town exhibited a summer neutral PET of 31.5 °C and a PET comfort-threshold interval of 27.5-35.4 °C (WANG et al. 2025). These comparisons indicate that the comfort range derived here is lower than that reported for typical adults, suggesting that older adults are more sensitive to thermal environments and have a reduced tolerance to high temperatures. This may be attributable to age-related declines in cutaneous vasomotor regulation and cardiopulmonary metabolic capacity, which increase susceptibility to thermal load. Nanjing's

typical hot-humid climate further aggravates thermal discomfort, as high temperature and high humidity jointly suppress evaporative heat dissipation and impose a dual burden on thermoregulatory mechanisms. Therefore, thermal-comfort design targeting older adults should move beyond universal thermal indexes and instead establish contextualized standards that account for both population characteristics and regional climate, which constitutes a key theoretical contribution of this study.

4.2 Impact Mechanisms of Landscape Elements on Elderly's Thermal Comfort

Both field measurements and simulations indicate that the influence of landscape elements on PET ranks as: tree-canopy coverage > planting pattern > landscape structures > pavement albedo, highlighting the dominant role of vegetation in thermal regulation through shading and evapotranspiration. This ranking also helps interpret the Qinhuai River sites: segments dominated by open hardscape and sparse canopy are expected to have the smallest area within the elderly PET range, whereas shaded tree belts and rest nodes supplemented by shade structures are more likely to meet the derived comfort threshold during hot periods.

1). Tree-canopy coverage significantly affects the proportion of the comfort area. When canopy coverage increases from 15% to 70%, the comfort-area ratio rises from 3.15% to 26.20%, showing a stable upward trend. This confirms that shading is the primary means of reducing PET; considering trade-offs among spatial function, ventilation, and management, increasing canopy coverage to ≥45% can be prioritized to achieve substantial gains, while higher coverage can further expand comfort areas but should be coordinated with accessibility and safety-maintenance requirements.

2). In terms of the area meeting the elderly PET comfort threshold, the ranking is: columnar pattern > enclosure pattern > clump pattern > row pattern. This may be because planting patterns modify airflow pathways and temperature gradients. The columnar configuration creates longitudinal ventilation bands via tree spacing, enabling a dynamic balance between shading and heat dissipation, and thus represents an optimal structural form for waterfront green spaces.

3). Although pavement albedo has a limited effect, light-colored, high-albedo materials can reduce surface temperature by 0.8-1.3 °C. However, increased reflectance may induce glare and cause visual discomfort for older adults; therefore, its application should be moderated and paired with localized shading.

4). Landscape structures create localized cool zones through structural shading and microventilation. The fully shaded pavilion reduces mean PET by 1.17 °C relative to the no-structure scenario, indicating that open shaded structures can balance radiative shielding with air circulation.

Table 7: Impact mechanisms of landscape elements on elderly's thermal comfort

Element	Attribute	Extent of area meeting the elderly nPET range
Vegetation	Tree-canopy coverage	70% ＞ 45% ＞ 15%
	Planting pattern	Columnar > Enclosure > Clump > Row
Pavement	Pavement material	Light granite > Colored concrete > Dark granite
Landscape structures	Structure type	Fully shaded pavilion > Semi-shaded pergola > None

4.3 Threshold-driven optimization strategies and designing implications

This study establishes a logical framework linking thermal comfort thresholds, landscape element responses, and design optimization. Guided by a threshold-driven strategy, waterfront green spaces can enhance elderly thermal comfort through the following approaches:

1). Vegetation configuration: moderately increase tree canopy coverage to at least 45%, and tailor planting form and layout to prevailing winds and site functions, using columnar or enclosure arrangements to support summer ventilation while reducing winter wind exposure.

2). Pavement selection: prioritize high-albedo materials, such as light granite, which can effectively reduce surface temperature in summer. Combined with the cooling effect of water bodies, this helps establish a multi-layer thermal buffering system.

3). Structure layout: appropriately arrange semi-open shaded structures such as pavilions and pergolas to both reduce direct solar exposure and facilitate air movement, thereby providing older adults with sustainable heat-refuge spaces.

Rather than proposing universally 'best' values, the recommendations above should be understood as a Qinhuai-calibrated design range that can be re-calibrated for other cities and user groups.

5 Conclusion

Using the waterfront green spaces along the Qinhuai River in Nanjing as a case, this study links field measurements, elderly thermal perception, and ENVI-met scenario testing to develop a threshold-driven workflow for age-friendly waterfront renewal. The main conclusions are as follows:

1). The summertime PET comfort interval for older adults is 22.29-27.85 °C, indicating higher sensitivity to thermal environments than the general population and the need to establish group-specific evaluation standards.

2). The influence strength of landscape elements on thermal comfort ranks as: tree-canopy coverage > planting pattern > landscape structures > pavement albedo. Among these, canopy coverage and planting pattern are the key drivers; vegetation-based measures outperform hard paving and structural elements. A 70% canopy with a columnar planting pattern achieves the highest regulation efficiency.

3). In terms of design strategy, vegetation-based regulation should be central, complemented by high-albedo pavements and well-ventilated, fully shaded pavilions/corridors, to form a microclimate with coordinated shading, heat dissipation, and air circulation.

Overall, the threshold-driven workflow developed from the Qinhuai River case supports evidence-based, age-friendly waterfront renewal by translating field-derived comfort information into design-operable simulation metrics; when applied elsewhere, the comfort threshold should be locally recalibrated to reflect climate, site form, and user perception.

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Do Trees Need Umbrellas? Using Raytracing to Assess the Heat Stress of Trees in Cities

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Abstract: Urban trees can face heat stress from surrounding built materials. This paper proposes a raytracing framework that integrates LiDAR and tree species trait data with a biophysical model to simulate hourly leaf temperatures and species-specific physiological responses. Simulating 25 scenarios with 147 trees reveals that the landscape vegetation ratio is more effective at reducing heat stress than façade vegetation. High landscape coverage decreased risk by 5.2%, whereas high façade vegetation could increase risk by up to 12.8%. This open source workflow enables landscape architects to make data-driven material decisions to enhance urban forest health.

Keywords: Tree health, heat stress, microclimate modelling, raytracing, urban forest

1 Introduction

As cities experience longer and hotter summers, landscape architects are increasingly called upon to design outdoor spaces with cooling benefits (AKBARI et al. 2001, BARTESAGHI KOC et al. 2018, WU et al. 2025). Tree planting and material selections are two effective design strategies to mitigate overheating in urban microclimates (HAYES et al. 2022). At the same time, high-albedo (i. e., highly reflective) materials such as metal roofing and single-ply membranes are common architectural strategies for lowering air temperatures (FALASCA et al. 2019, SCHNEIDER et al. 2023). While the combination of materials with high-albedo and denser tree canopies could potentially improve urban temperature conditions (ELGENDY et al. 2025), high-albedo materials can induce acute heat stress in nearby trees (ERELL et al. 2014), even in cool temperate cities (KONARSKA et al. 2023, RISSANEN et al. 2024).

Tools such as ENVI-met (BRUSE & FLEER 1998) allow researchers and designers to investigate air temperature and outdoor thermal comfort under different planting scenarios, accounting for interactions among climate, trees, buildings, pavement, and other vegetated surfaces. Yet these tools come at a high cost, making them less accessible to researchers and landscape architects. While ENVI-met provides databases for materials and vegetation processes, users frequently rely on generic inputs and simplified canopy models, which can limit the authenticity of simulations in reflecting tree structures and site-specific surface material conditions. This gap limits landscape architects' capacity to make data-driven decisions about strategies that influence not only human thermal comfort but also the health of urban trees.

This paper proposes a modelling procedure capable of producing spatially detailed, temporally frequent data on the potential heat stress of trees. Specifically, we use datasets familiar to landscape architects (e. g., point cloud and tree species trait data) alongside high-fidelity, physics-based simulations developed by building and urban scientists (e. g., raytracing).

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2 Assessing Heat Stress of Urban Trees

This method deploys a coupled surface-leaf-soil biophysical model to evaluate urban tree heat stress under alternative surface material scenarios (Fig. 1). The site model, described in Sec. 2.1, simulates hourly leaf temperature by integrating: high fidelity raytracing through Radiance (LARSON & SHAKESPEARE 1998) (Sec. 2.2), landscape and façade surface energy balance (Sec. 2.3), and the resulting biophysical stress on trees in the site (Sec. 2.4). The workflow supports scenario comparison for both landscape and façade materials by propagating the same material properties from raytracing to the biophysical calculations.

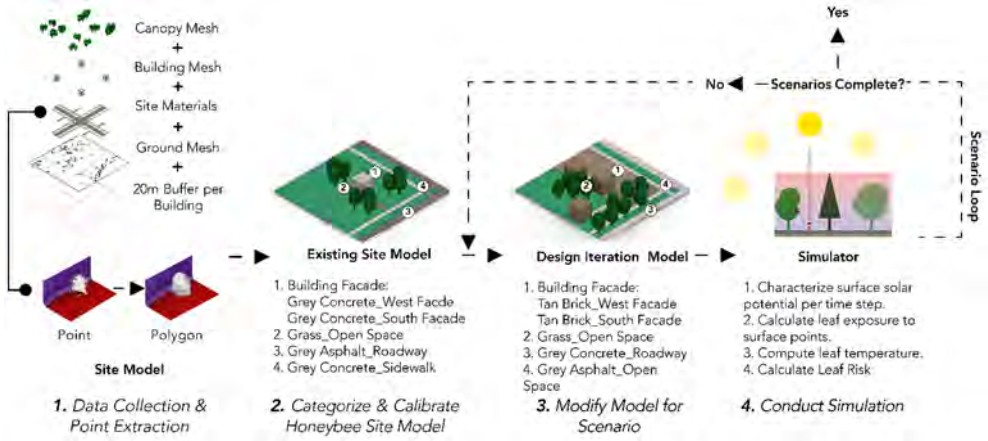

Fig. 1: The workflow for the project begins from data collection, digital elements assembly to the simulation loop phase

2.1 Digital Sandbox Assembly

The study site is in Winnipeg, Canada (49.90°N, 97.23°W). A digital base model was assembled to represent building volumes, façade and ground materials, with 147 on-site trees representing 33 species common to the region. Opaque surfaces were parameterized with material properties required for radiative and thermal calculations, emphasizing shortwave albedo (α) and longwave emissivity (ε), and materials were grouped as landscape (horizontal ground) or façade (vertical wall surfaces). Field survey is combined with building models and aerial laser surveys (CITY OF WINNIPEG 2021) of site vegetation to construct this base model (Fig. 2).

This base model represents the site's physical conditions (e. g., road networks, buildings, trees and other vegetated surfaces). It is semantically descriptive of surface materials (e. g., short grass, asphalt, grey cement pavers). This model was then translated into a Radiance project with a 1x1 meter point grid above the ground surface for physically accurate raytracing and the evaluation of surface solar gains within the model. The simulation produces a gridded time-series of direct beam irradiance and diffuse irradiance (i. e., surface solar potentials, or SP). These were then used to characterize the thermal environment around each tree.

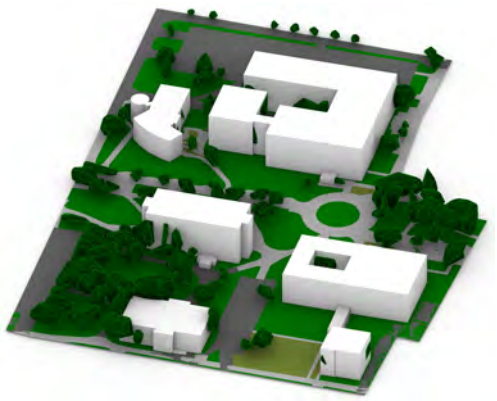

Fig. 2:
A 3D isometric representation (from the Southeast view) of the digital site simulation model

2.2 Raytracing Model Setup

To assess leaf risk (i. e., heat stress on foliage), 25 scenarios with fixed geometry and updated optical and thermal properties were defined and simulated based on combinations of landscape vegetation ratio (LVR, the percentage of horizontal space covered by vegetation) and façade vegetation ratio (FVR, the percentage of façade space covered by vegetation). For each scenario, the Radiance outputs were coupled to a simple surface energy balance to estimate surface and air temperatures and mean radiant temperature (MRT, including reflected shortwave from bright pavements). For each tree, a leaf-energy balance (with species Leaf Area Index and leaf traits) yields leaf temperature and transpiration; soil moisture is estimated from surface permeability and irrigation assumptions.

2.2.1 Tree – "Sensor" Mapping

A total of 4,325 sample points were generated in the model and used as the simulation "sensors" between 3D radiative transfer and tree-scale biophysics. Each tree was assigned the nearest grid in a 3D Euclidean space. Hourly irradiance components simulated at the sensor were then attributed to the tree and used to drive the subsequent surface and leaf energy balance calculations. This nearest-sensor coupling preserves spatial heterogeneity from buildings and surface materials while remaining computationally tractable across many trees and scenarios.

Species-specific physiological parameters were compiled from published literature and the TRY Plant Trait Database (KATTGE et al. 2020) and applied consistently across scenarios. Key parameters included leaf absorptivity (α_{leaf}), leaf emissivity ($\varepsilon_{\text{leaf}}$), maximum stomatal conductance ($g_{s,max}$) and stress response thresholds. Parameters governing radiation interception, specifically the fraction of downwelling radiation intercepted from above and below, were assigned based on LiDAR-derived tree crown architecture. Sky view factor (SVF) was computed individually for each tree using an average of two vectors: horizontal and south facing but tilted 45˚ upward). SVF was used to characterize the local radiative environment. SVF represents the fraction of the sky hemisphere visible from a point and influences both longwave radiation exchange with the atmosphere and MRT.

2.2.2 Radiative Transfer and Irradiance Components

Hourly irradiance fields were simulated in Radiance 5.2 (LBNL-ETA 2025) using a two-phase, direct-diffuse workflow to resolve the radiative environment at each sensor point. Here, (K) denotes shortwave (solar) irradiance (Wm^{-2}). Upwelling shortwave at a sensor was approximated post-raytracing using local material albedo: $K_{\uparrow(i,t)} = \alpha_i \, K_{\downarrow(i,t)}$. Longwave radiation was calculated from atmospheric conditions and surface temperatures rather than explicit raytracing. Downwelling longwave from the sky ($L_{\downarrow(i,t)}$) was computed from air temperature and relative humidity using standard atmospheric emissivity relationships. Upwelling longwave from surfaces ($L_{\uparrow(i,t)}$) was calculated as $L_{\uparrow} = \varepsilon \, \sigma \, T_{\text{surf}}^4$, where surface temperature was determined from the ground energy balance (Section 2.4). All scenarios used identical geometry, sensor points, and Radiance settings, so differences in radiation forcing reflect only changes in material properties (α), (ε). These shortwave and longwave components were then used to compute net radiation in the ground and leaf energy balances.

2.3 Material Scenario Construction

Material scenarios were constructed to isolate the influence of urban surface properties on tree radiative forcing and physiological stress. A factorial design was employed with five levels each for the landscape naturalness ratio ($r_L \in \{0,0.25,0.5,0.75,1.0\}$) and façade naturalness ratio ($r_F \in \{0,0.25,0.5,0.75,1.0\}$), yielding 25 scenarios (Fig. 3). The naturalness ratio controls the fraction of surfaces assigned vegetation-like materials (high emissivity, moderate albedo) versus mineral/synthetic materials (lower albedo, representing concrete, asphalt, or brick).

Surface materials were assigned to landscape and façade elements via grid identifiers carried through the Radiance pipeline, enabling consistent mapping between simulated irradiance outputs and the underlying surfaces. Alternative scenarios were generated by swapping material assignments for selected landscape and/or façade elements while holding all other inputs constant (geometry, tree locations, sensor grid, and weather). Each scenario was then re-simulated in Radiance using the same direct-diffuse workflow to produce comparable hourly irradiance components at each sensor.

Scenario effects enter the energy balances primarily through shortwave absorption and longwave exchange. For example, the net shortwave at the surface can be expressed as:

$$K_{\text{net}}(t) = (1 - \alpha) \, K_{\downarrow}(t) - K_{\uparrow}(t)$$

Changing (α) modifies both local absorption and (via $(K_{\uparrow})$) the reflected field experienced by nearby trees. Scenario outputs were stored as sensor-grid time series and mapped to trees for biophysical evaluation.

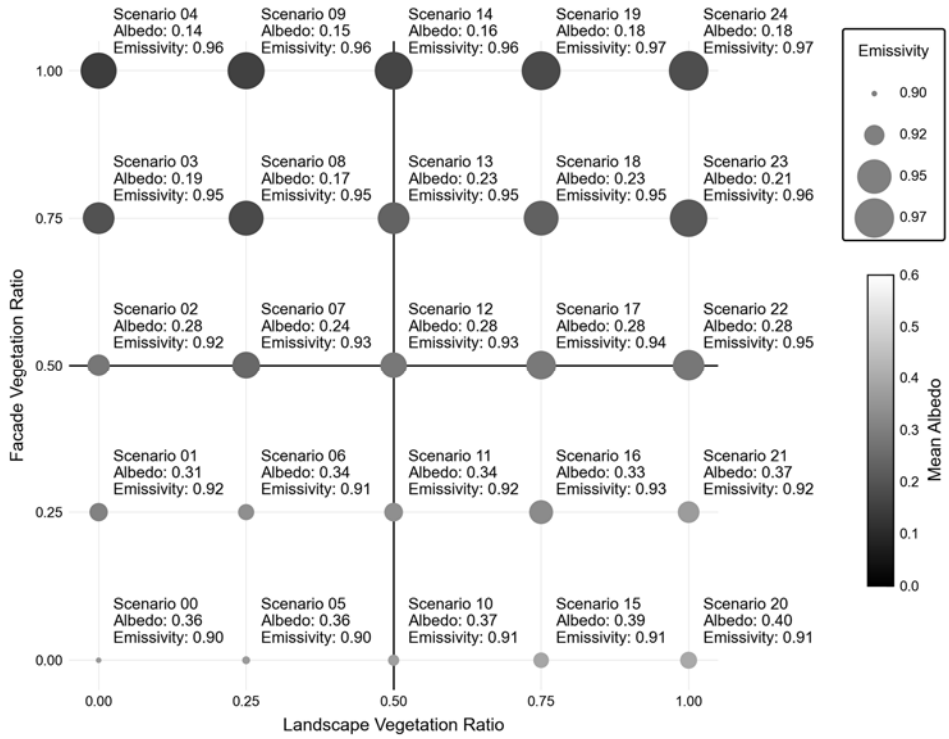

Fig. 3: The concept between the scenario development. Ratios refer to the percentage of total surfaces that are considered natural or not (i. e., concrete to grass).

2.4 Biophysical Stress

Tree stress was evaluated for the warmest week of the year (168 h), identified using a 7-day running mean of dry-bulb air temperature. For each tree and scenario, hourly ground temperature (T_g) was estimated using a one-layer surface energy balance accounting for thermal mass, absorbed shortwave (modulated by albedo), longwave exchange (modulated by emissivity), and sensible and latent heat fluxes. Material-specific heat capacity and evaporation factors (0 for impervious, 0.3-0.8 for pervious/vegetated surfaces) were assigned based on surface type. Leaf temperature (T_{leaf}) was then computed using the steady-state Canopy Energy Balance (CEB) model of Li et al. (2023), which takes scenario-specific shortwave irradiance and ground temperature as inputs. Material albedo affects leaf temperature through reflected shortwave, while emissivity affects it through ground cooling and upwelling longwave radiation.

We define stress (i. e., tree risk index) as the number of hours a leaf is above 30˚C. In this study, we use 30˚C heat stress as an efficiency risk (i. e., when leaf temperature is outside the optimal range) rather than a survival risk (DIAO et al. 2024). This model can also be parametrized to a higher temperature threshold (e. g., 42˚C) to avoid overly conservative simulations or to accommodate warmer climate conditions than those in Winnipeg. Scenario performance (i. e., biophysical stress of trees) was evaluated as stress reduction relative to the centre scenario (50%, 50%) in scenario 12 (Fig. 3).

3 Results and Discussion

3.1 Site Condition and Leaf Temperature Baseline

The site experienced a consistent daily pattern of ambient air temperature variation, except on July 1, 2025, when the temperature dropped to approximately 10°C. The median leaf temperature fluctuates in tandem with air temperature. SVF ranges from 0.10 to 0.19 across the site, reflecting the heterogeneous built environment surrounding each tree. Overall, the air temperature is marginally above the median leaf temperature during the day and below it at night. These results indicate that our simulated leaf temperature is responding well to the external climate variables.

3.2 Comparative Analysis of 25 Scenarios

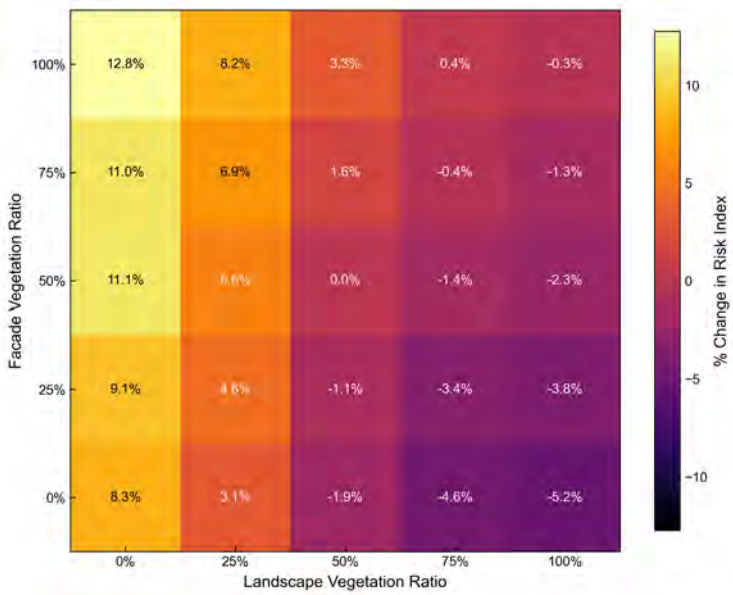

Fig. 4: Relative change in leaf risk in 25 simulated scenarios. The percent change was computed based on a 50/50 vegetation ratio (i. e., no change in risk index) in both the landscape and façade spaces.

Expectedly, as the LVR increases, tree risk decreases. This trend is consistent across façade FVRs (Fig. 4). We observe the greatest risk reduction when LVR is at its peak and when façade surfaces have minimal vegetation cover. However, for the same LVR, an increase in FVR (i. e., more vegetation cover on a given façade) will increase tree risk. In fact, the greatest increase in the risk index (+12.8%) occurs when FVR is 100%, and LVR is 0%.

This result is likely due to higher levels of landscape albedo (i. e., concrete is more reflective than vegetation) when ground vegetation cover is low. It is worth noting that the current implementation did not account for the emissivity of façade materials on nearby trees. It ac-

counted only for albedo during raytracing. Therefore, further work is needed to extend the leaf temperature model to account for multiple sources of exposure in longwave radiant transfer. There is discussion in the literature (SUSCA et al. 2022) on the impact of façade vegetation on mitigating heat in urban microclimates, and we identify the impact of emissivity as a current gap in this research.

3.3 Sensitivity Analysis

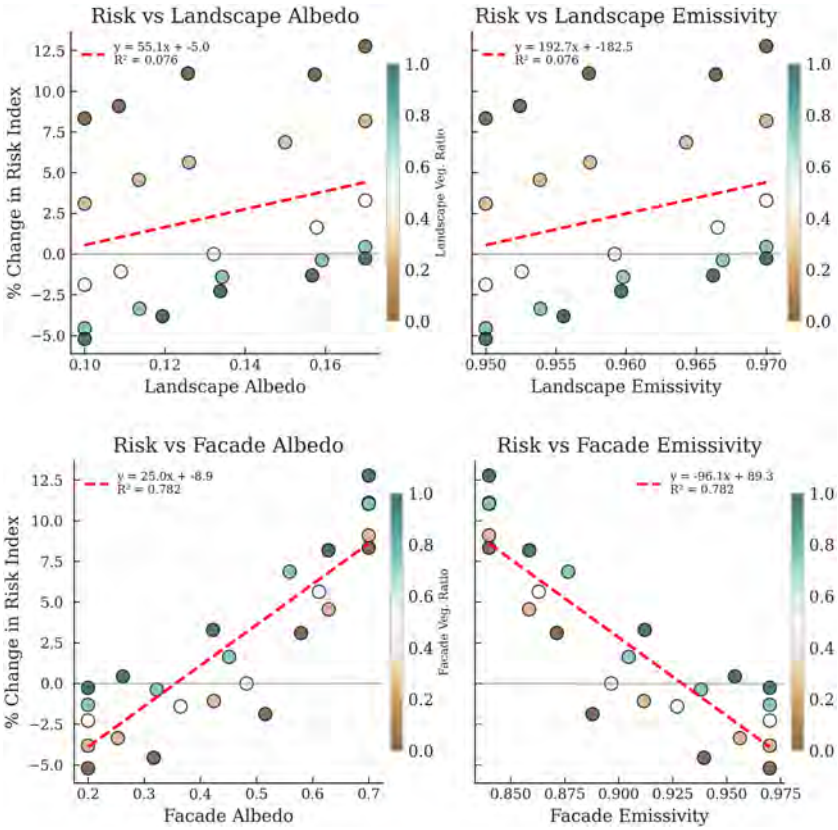

Fig. 5: Sensitivity analysis of the albedo and emissivity of the surfaces to the risk index

A sensitivity analysis further reveals how heat risk responds to different levels of material albedo and emissivity (Fig. 5). While facade emissivity is included, the relationship is superficial, as the model currently does not physically link the emissivity of the facade materials to leaf temperature. It is apparent that increases in albedo and emissivity lead to higher heat stress. With regards to the landscape material shift, a general linear trend can be observed across the landscape vegetation ratio spectrum (0 to 1, in Fig. 5). While the overall regression is weak, when fitted, a similar slope independently arises for each group. This is important to note, as the model accounts for ground temperature differently across material types, suggesting that it is not a more significant influence than emissivity or albedo alone. Future research is needed to follow up on this observation.

4 Conclusion and Outlook

This study integrates LiDAR-derived tree models, species trait data, and raytracing to simulate how material selections and planting patterns influence tree health. Crucially, the LVR emerged as the most effective strategy for mitigating heat stress, with the best-performing scenario reducing the tree risk index by 5.2% relative to the reference condition. This highlights a design paradox: increasing the FVR, intended to provide cooling, can inadvertently increase tree risk by up to 12.8% in certain configurations, due to the façade's higher albedo relative to conventional materials. This paper introduces an open-source "digital sandbox" that allows practitioners to test and measure the effects of materials and planting prior to construction, in contrast to commercial tools like ENVI-Met. Yet the unexpected increase in tree efficiency risk associated with façade vegetation warrants further research into façade emissivity and drought stress. Future work should make this model more accessible particularly to practitioners and expand the species-specific physiological parameters and validate the model across diverse climatic regions beyond Winnipeg.

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A Digital Optimization Method for Green Space in Old Urban Residential Area Aimed at Thermal Comfort

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Abstract: Improving the microclimate and thermal comfort of old urban residential areas is a key issue in global climate change and urban renewal. This study investigates a typical old urban residential area in Nanjing and proposes a digital workflow integrating parametric modelling, microclimate simulation, and multi-objective genetic algorithm optimization. The objective is to optimize the comprehensive Universal Thermal Climate Index (UTCI) for both summer and winter. The results show that, under the conditions of this study, thermal comfort is optimal when the green coverage ratio is 26% and tree cover is 33%. Among vegetation parameters, tree crown width has the strongest influence on thermal comfort, followed by the shrub-to-grass ratio and leaf area index. The optimal configuration is a shrub-to-grass ratio of 50%:50%, a tree crown width of 7 m, and a leaf area index of 3. The proposed method provides quantitative and intelligent support for green space retrofitting and sustainable urban renewal in hot-summer and cold-winter regions.

Keywords: Thermal comfort, green space, ENVI-met, microclimate simulation, parametric modelling

1 Introduction

Climate change has intensified the urban heat island effect, especially in hot-summer and cold-winter regions of China. Old urban residential areas often suffer from poor thermal environments due to high building density and insufficient green space. As a result, residents experience low thermal comfort.

Previous studies have shown that green space, particularly tree shading, can effectively improve urban thermal conditions. However, most studies focus on large spatial scales or single seasons. Research addressing seasonal differences in thermal comfort and fine-scale green space regulation in old urban residential areas remains limited. Existing studies combining microclimate simulation and genetic algorithms mainly emphasize overall spatial layouts and rarely consider multi-season optimization.

This study aims to develop a digital green space optimization method for old urban residential areas by integrating genetic algorithms with microclimate simulation. Seasonal differences in thermal comfort are explicitly considered. The objectives are to: (1) Evaluate the effects of green space quantity and configuration on thermal comfort. (2) Establish a multi-objective optimization model for summer and winter conditions. (3) Propose practical strategies for green space renewal and thermal environment improvement.

The study seeks to support dynamic green space optimization and provide a scientific basis for microclimate improvement in old urban residential areas.

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2 Study Area and Data Sources

Nanhu neighbourhood in Nanjing was selected as the study area (Figure 1). Nanjing is located in a hot-summer and cold-winter climatic zone, with hot and humid summers and cold, damp winters. Nanhu is a typical old urban residential area with dense buildings and fragmented green space. Summer thermal discomfort is prominent. Three types of data were used: meteorological data, urban morphology data, and vegetation data. Meteorological data include air temperature, relative humidity, wind speed and direction, and solar radiation. Urban morphology data were obtained through field surveys and low-altitude aerial photography. Vegetation data were collected through on-site measurements and include leaf area index and clearance height.

Fig. 1: Location of the study area

3 Methods

A digital optimization framework was developed for green space in old urban residential areas (Figure 2). The framework integrates multi-source data, parametric modelling, microclimate simulation, and multi-objective genetic algorithms. Thermal comfort in summer and winter is evaluated using the Universal Thermal Climate Index (UTCI).

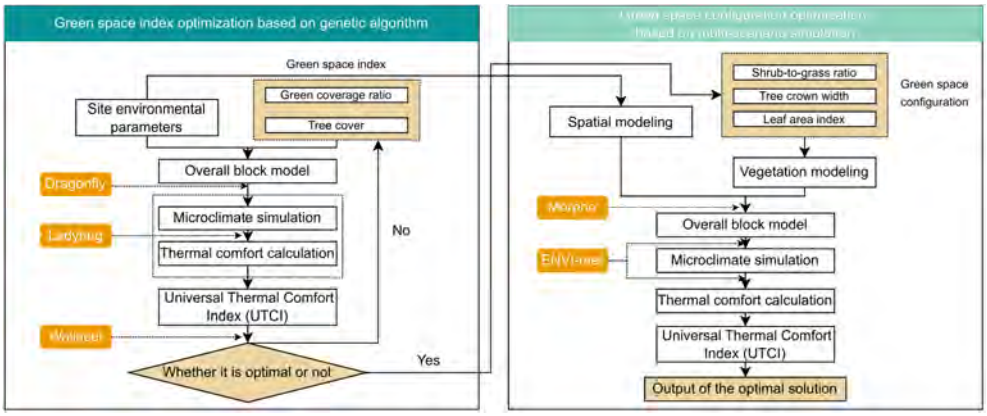


Fig. 2: Methodological framework

3.1 Determination of Key Parameters

Five parameters were selected to represent green space quantity and configuration: green coverage ratio, tree cover, shrub-to-grass ratio, tree crown width, and leaf area index. These parameters form a control framework for thermal comfort regulation (Table 1).

Table 1: Definition and calculation of green space parameters

Category	Factor	Formula	Remarks
Geen space indicator	Green space ratio (G_R)	$G_R = \frac{A_G}{A_T} \times 100\%$	G_R represents the green space ratio; A_G represents the total area of all land used for greening, with the unit being m^2; A_T represents the total land area of the studied region, with the unit being m^2.
	Tree coverage rate (C_{TR})	$C_{TR} = \frac{A_{CP}}{A_T} \times 100\%$	C_{TR} represents the tree coverage rate; A_{CP} is the projected area of the tree crown, that is, the total area covered by the vertical projection of the tree crown on the ground, with the unit of m^2.
Geen space configuration	Srub-herb ratio (R_{SH})	$R_{SH} = \frac{A_S \times 100\%}{A_G \times 100\%}$	R_{SH} represents the ratio of shrubs to grass; A_S represents the total area covered by shrubs on the ground, with the unit being m^2.
	Tree crown width (C_T)	$C_T = \frac{W_E + W_N}{2}$	C_T represents the crown width of trees, with the unit being m; W_E represents the maximum horizontal projection width of the tree crown in the east-west direction, with the unit being m; W_N represents the maximum horizontal projection width of the tree crown in the north-south direction, with the unit being m.
	Leaf Area Index (LAI)	–	–

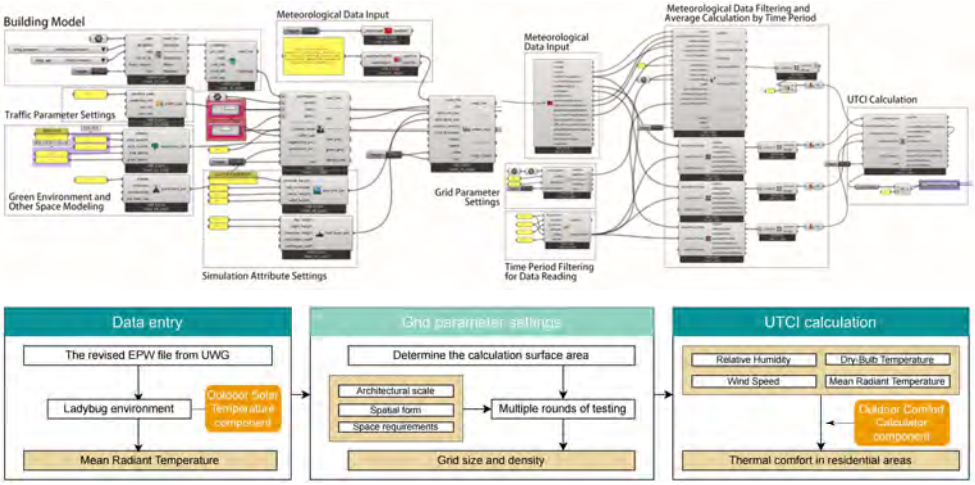


Fig. 3: Workflow and component diagram

3.2 Performance Simulation Based on Ladybug Tools

A parametric microclimate model was built using Rhino and Grasshopper with Ladybug Tools. Buildings, roads, ground surfaces, and vegetation were integrated into the model. Meteorological data were corrected using the Urban Weather Generator (UWG). Block-scale thermal comfort simulations were then conducted. The workflow is shown in Figure 3.

3.3 Multi-objective Optimization

Multi-objective optimization was conducted on the Grasshopper platform using the Wallacei plugin. Summer and winter UTCI values were defined as objective functions. A Pareto-optimal solution set was obtained through genetic algorithm iteration. The optimization process is shown in Figure 4.

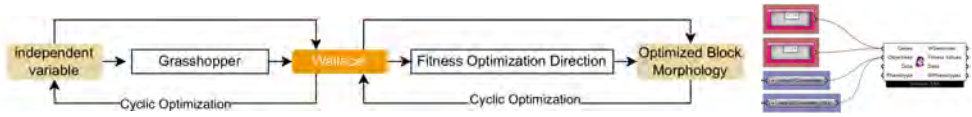


Fig. 4: Multi-objective optimization workflow and component diagram

3.4 Microclimate Simulation Based on ENVI-met

ENVI-met simulations were conducted based on the optimized layouts. Three-dimensional models were built using the Morpho component. Tree parameters, including tree height, tree crown width, branch height, and leaf area density (LAD), were defined using the Albero module. Leaf area index was converted to LAD following the method of LALIC et al. (2004).

Based on shrub-to-grass ratio, tree crown width, and leaf area index, 27 simulation scenarios were constructed (Table 2). UTCI values were calculated at a height of 1.4 m using Morpho–ENVI-met coupled simulations (Figure 5).

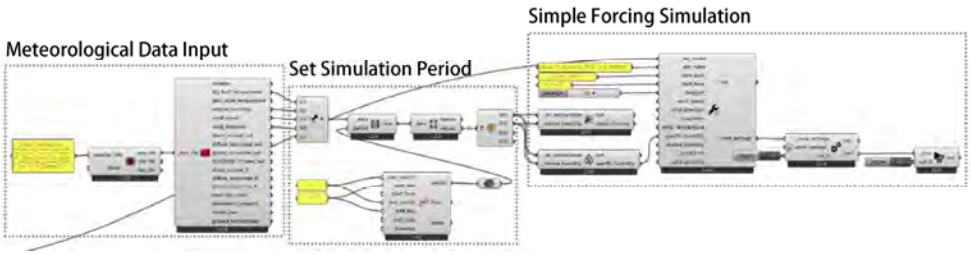
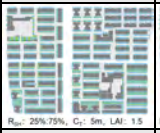
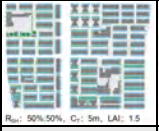
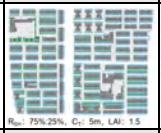
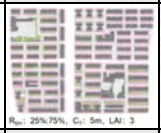
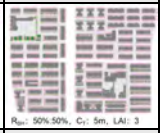
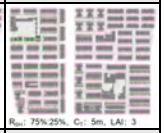


Fig. 5: Microclimate simulation component diagram

Table 2: The configuration of each scenario layout

	A1	**B1**	**C1**	**A2**	**B2**	**C2**
Plan View						
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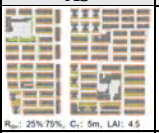
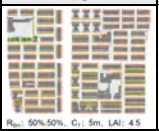
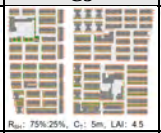
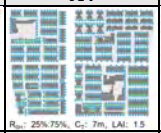
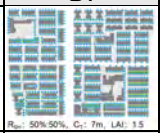
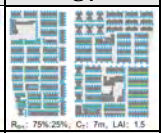
Plan View						
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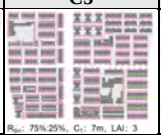
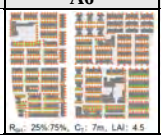
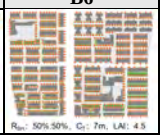
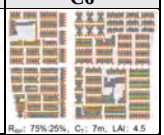
Plan View						
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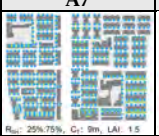
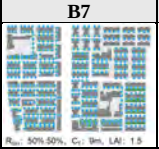
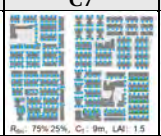
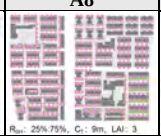
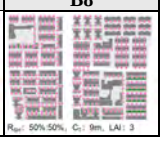
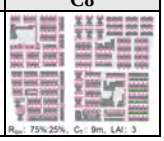
Plan View						
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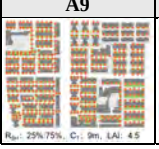
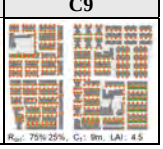
Plan View						

4 Results and Discussion

The multi-objective genetic algorithm exhibited good convergence over 50 generations with a total of 1,000 candidate solutions, demonstrating the robustness and stability of the optimization process. The UTCI target values for both summer and winter gradually stabilized throughout the iterations, indicating that the model reliably captures the seasonal thermal dynamics. Based on clustering analysis of the Pareto-optimal solution set, solution a20 was identified as the optimal design (Table 3), corresponding to a green coverage ratio of 26% and a tree cover of 33%, which achieves the best balance of thermal comfort between winter and summer. Pearson correlation analysis further revealed that tree cover was significantly negatively correlated with summer UTCI ($r = -0.721$, $p < 0.01$), while exhibiting a moderate positive correlation with winter UTCI ($r = 0.493$, $p < 0.01$). These results indicate that trees play a critical role in mitigating heat stress during summer through shading and evapotranspiration, while slightly reducing solar gain and shading in winter. In contrast, the effect of green coverage ratio was relatively weak and showed no significant correlation with tree cover, suggesting that these two factors independently and controllably contribute to seasonal thermal regulation.

Table 3: Simulation results of the combined UTCI for winter and summer across 25 typical sample cases

Code	G_R	C_{TR}	UTCI-summer/°C	UTCI-winter/°C	ΔUTCIT/°C	Code	G_R	C_{TR}	UTCI-summer/°C	UTCI-winter/°C	ΔUTCIT/°C
a1	21%	57%	35.08	1.679	1.758	**a14**	24%	53%	35.07	1.672	1.742
a2	21%	60%	35.079	1.678	1.757	**a15**	24%	12%	35.048	1.666	1.715
a3	20%	60%	35.079	1.678	1.757	**a16**	21%	59%	35.08	1.679	1.758
a4	23%	13%	35.047	1.666	1.713	**a17**	22%	53%	35.08	1.672	1.751
a5	23%	53%	35.08	1.672	1.751	**a18**	20%	53%	35.08	1.679	1.758
a6	24%	52%	35.07	1.672	1.742	**a19**	20%	52%	35.08	1.679	1.759
a7	22%	13%	35.057	1.666	1.724	**a20**	26%	33%	35.073	1.665	1.738
a8	23%	14%	35.057	1.666	1.724	**a21**	20%	50%	35.08	1.672	1.751
a9	21%	50%	35.08	1.672	1.751	**a22**	24%	51%	35.07	1.672	1.742
a10	20%	54%	35.08	1.679	1.759	**a23**	24%	49%	35.072	1.665	1.737
a11	24%	51%	35.07	1.672	1.742	**a24**	23%	43%	35.07	1.672	1.742
a12	24%	13%	35.048	1.666	1.714	**a25**	26%	13%	35.047	1.666	1.713
a13	24%	50%	35.071	1.672	1.743						

Based on the optimal green coverage ratio, 27 different configuration scenarios were simulated using parametric modelling and microclimate simulation (Figure 5) to systematically assess their effects on seasonal thermal comfort. The results indicate that shrub-to-grass ratio, tree crown width, and leaf area index (LAI) all exert significant influences on thermal comfort in both winter and summer, highlighting the importance of both horizontal and vertical vegetation structures. A shrub-to-grass ratio of 50%:50% was found to achieve the most balanced thermal environment across the two seasons, effectively combining shading, evapotranspiration, and surface heat regulation. Increasing tree crown width enhances shading and cooling, but an excessive width (9 m) may impede natural ventilation, potentially reducing summer thermal comfort. LAI exhibits a threshold effect: values that are too low provide insufficient cooling, while excessively high values can restrict air circulation and reduce

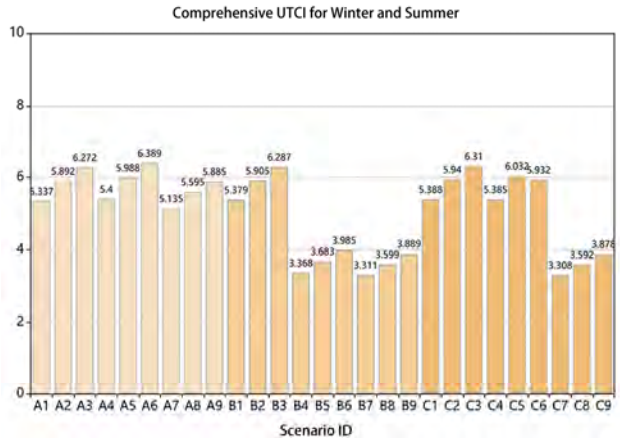
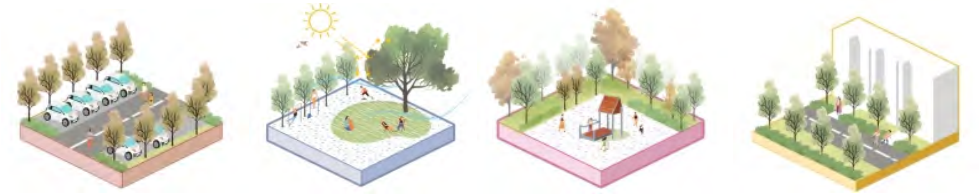


Fig. 5:
Bar chart of the combined average thermal comfort for winter and summer

overall comfort. ANOVA results demonstrate that tree crown width has the most significant effect on seasonal thermal comfort ($F = 10.373$, $p < 0.001$), followed by shrub-to-grass ratio ($F = 9.219$, $p < 0.001$), whereas the effect of LAI is comparatively weak ($p > 0.05$). Integrated analysis of these factors identifies the optimal green space configuration as a shrub-to-grass ratio of 50%:50%, crown width of 7 m, and LAI of 3.

From a seasonal perspective, tree cover has the strongest cooling effect in summer but may slightly reduce thermal comfort in winter due to shading, which is consistent with the findings of SNIR et al. (2016) and CHENG et al. (2011). The green coverage ratio primarily improves summer comfort through evapotranspiration, with limited effects in winter (BOWLER et al. 2010). The low correlation between trees and ground vegetation indicates that the two are independent yet complementary in microclimate simulation. The moderate positive correlation of UTCI between winter and summer reveals seasonal conflicts in thermal comfort (EDUARDO & PETER 2012), suggesting that urban greening should seek a dynamic balance between the two seasons. This study further demonstrates the quantitative importance of the independent yet complementary roles of trees and ground vegetation in seasonal thermal regulation. It highlights how vertical and horizontal vegetation structures contribute differently to microclimate modulation. Unlike previous research that often focuses on a single season or a single indicator, our analysis integrates winter and summer UTCI with multi-factor green space configuration simulations, providing a more systematic and actionable basis for optimizing green space in old urban residential areas. These results offer practical guidance for achieving a dynamic balance between summer cooling and winter solar access within limited urban spaces.

Based on the hierarchy of factors and seasonal response characteristics, this study proposes three principles for green space optimization: (1) Parametric coordinated control: dynamically balancing green coverage ratio and tree cover to regulate thermal comfort in both winter and summer, ensuring that vegetation contributes effectively to cooling in summer while maintaining adequate solar access in winter. Under the optimized conditions of this study, the green coverage ratio of 26% and tree cover of 33% were identified as the optimal combination; (2) Spatial differentiation configuration (Figure 6): adopting a “dense planting at the periphery, open space at the centre” layout. The recommended tree canopy widths of 7 m and 9 m, which performed well in both winter and summer, support the formation of continuous shading and ventilation corridors. Meanwhile, maintaining the overall green coverage ratio around 26% ensures effective airflow organization and preserves visual and spatial openness



(a) Ecological parking lot “Greening in building clusters”

(b) Public activity area “Tree array + large arbors”

(c) Plaza space “Dense planting on the periphery + open space in the center”

(d) Residential inter-block green space “Greening in gaps”

Fig. 6: Schematic diagram of green space optimization strategies for different zones

for different activity zones; (3) Seasonal dynamic pruning: implementing differentiated pruning and maintenance for evergreen and deciduous trees to regulate canopy width and LAI. Based on the optimal scenario (shrub-grass ratio 50%:50%, canopy width 7 m, LAI 3), management should prioritize canopy width and shrub-grass ratio adjustment, while moderately controlling LAI – particularly in summer – to balance seasonal shading and solar access and maintain long-term tree health. Collectively, these strategies coordinate green quantity, ventilation, and daylighting within the limited space of old urban residential areas to improve year-round thermal comfort and microclimate performance.

5 Conclusion

This study develops a digital optimization framework integrating parametric modeling, microclimate simulation, and multi-objective genetic algorithms to improve year-round thermal comfort in old urban residential areas in hot-summer and cold-winter regions. Under the conditions of this study, the optimal green coverage ratio is 26% and tree cover is 33%. The optimal configuration is a shrub-to-grass ratio of 50%:50%, a tree crown width of 7 m, and a leaf area index of 3. The influence of vegetation parameters follows the order: tree crown width > shrub-to-grass ratio > leaf area index. Limitations include reliance on simulation data, simplified building materials and terrain, and the exclusion of plant species and green space morphology. Future studies should combine field measurements with refined models and multi-parameter optimization to improve reliability and applicability.

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Identifying the Coolest Trees on the Block: Drone-Based Thermal Image Analysis of Tree Crown Temperatures

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Abstract: Human-induced climate change is causing increasing temperatures, changing rainfall regimes, increased frequency of natural disasters and extreme weather, and loss of biodiversity. Mitigating climate change effects in cities, where higher temperatures and the urban heat island (UHI) effect are increasingly impacting citizen health, is becoming more difficult. Varied strategies are needed to alleviate complications due to UHI and climate change. Trees as nature-based solutions are one of the most popular and easiest mitigation measures to implement. This study investigated drone thermal images measuring the surface temperature of tree crowns, open grass, gravel paths, and shadows over grassy areas and gravel paths in the Enea Tree museum, an arboretum in Rapperswil-Jona, Switzerland. We wanted to identify tree species with consistent temperature differences compared to ambient air temperature (always cooler or always warmer than other species) in different weather conditions. In addition, we compared thermal properties of different shaded vs. unshaded surface covers. We found that tree species significantly differed in their crown surface temperatures. *Parrotia persica* and *Acer palmatum* were warmer than air temperature across all dates, while *Platanus* x *hispanica* was always cooler than air temperature. Surface temperatures of trees were correlated with the specific leaf area (SLA) with trees with higher SLAs and thus thinner leaves having on average a higher crown-surface temperature. The largest cooling effects were measured in tree shadows over grass. Importantly, shadows over gravel paths were found to be only slightly cooler than the ambient air and did therefore not contribute to microclimatic cooling. Our method can help planners identify suitable tree species and ground covers to reduce urban heat and promote cooling, especially in cities and climates where predicted temperature and rainfall changes could affect long-term survival of traditionally used tree species.

Keywords: Drone, thermal, tree crown, grass, shade

1 Introduction

Human-induced climate change is leading to increasing temperatures, rising sea levels, changing rainfall regimes, increasing frequency of natural disasters and extreme weather events, and, ultimately, loss of biodiversity (IPCC 2023). Mitigation of all possible scenarios is becoming more difficult, especially in cities dealing with these pressures as well as with increased population and housing density (GRIMM et al. 2008). Heat related deaths are increasing in recent years, especially in cities affected by the urban heat island (UHI) effect, which is reduced nighttime cooling in urban areas compared to natural or rural surroundings (OKE 1982, JOHNSON & WILSON 2009). While it is important to develop varied strategies to alleviate complications due to intensified UHI effects, trees as nature-based solutions have

become one of the most popular and easiest methods to mitigate heating effects, especially in urban environments with high levels of sealed surfaces (KLEEREKOPER et al. 2012, ETTINGER et al. 2024).

UHI effects can be lessened, and microclimate temperatures reduced with vegetation through removing sealed surfaces and planting ground cover, trees, and shrubs, as well as through green roofs and ground-based green facades. Planting trees can have the largest impacts and have been shown to reduce physiological equivalent temperature (PET) by 10-13% in large cities, representing a stronger effect for pedestrians than green roofs and facades (ZÖLCH et al. 2016). Trees have been found to reduce land surface temperature by 8-12°C on average in Central European cities (SCHWAAB et al. 2021). Cooling from trees is due to shading and evapotranspiration, with shade capable of decreasing the surface temperatures of natural and man-made surfaces by significant amounts (SHARMIN et al. 2023). Recent studies also highlight possible health benefits of larger, connected groupings of trees, especially in cities (CHI et al. 2025). However, the criteria and data to choose the best tree species and combinations of tree species as nature-based solutions for climate change mitigation for a given environmental situation are often not well defined or consistently available.

Adding greenspace in cities is widely accepted by the public (KLEEREKOPER et al. 2012) and thus selection of suitable plant functional types and species becomes important. Research has identified different tree morphologies influencing the cooling effects, including crown shape, canopy size and density, features of the leaves, as well as configurations of plantings (GEORGI & DIMITRIOU 2010, SHAHIDAN 2015). Canopy density, leaf area index (LAI), and leaf area density are regarded as having the greatest influence on surface cooling by trees (ARMSON et al. 2013, RAHMAN et al. 2015, HELLETSGRUBER et al. 2020). Many studies have also found that different species, as well as their locations, can lead to different levels of cooling (RAHMAN et al. 2015, RAHMAN et al. 2019, HELLETSGRUBER et al. 2020, MORAKINYO et al. 2020). It is therefore imperative to choose the correct species to plant in the right geographic location to best improve the local cooling effects (ZÖLCH et al. 2016, MORAKINYO et al. 2020).

This study investigated the effectiveness of an unmanned aerial vehicle (UAV or drone) equipped with a thermal camera to measure the surface temperature of tree crowns, open grass, gravel paths, and tree shadows over grassy areas and gravel paths on three summer days in an arboretum in Rapperswil-Jona, Switzerland. The goal was to determine if – under environmentally similar conditions – certain tree species had consistent temperature differences with ambient air temperature (always cooler or always warmer than other species) on days with different weather conditions. We also investigated how specific leaf area influences these tree crown surface temperatures.

1.1 Study Area

The research was conducted at the Enea Tree Museum (ETM; 47.22°N, 8.87°E) in Rapperswil-Jona, St. Gallen, Switzerland (www.enea.ch/baummuseum/). This arboretum is a 75,000 m^2 park on the property of the headquarters of Enea, GmbH, near Lake Zurich. Tree species in this arboretum are frequently used in landscape architecture projects. Trees in the park are mostly over 20 years old, with individual trees over 100 years old. This study focused on 192 individual trees from 42 different species (Figure 1). The trees are managed year-round through watering, fertilization, and pruning. Rapperswil-Jona is in eastern Switzerland

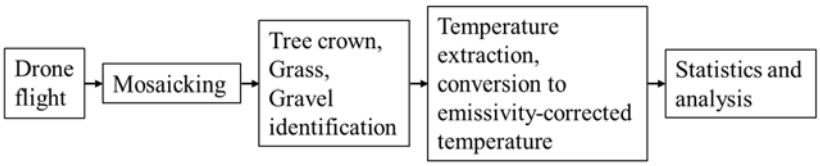
with a yearly precipitation of 1381 mm (www.hydrodaten.sg.ch) and average annual temperature of 10.7°C (SCHMUTZ 2024). This location allowed for the study to be conducted in a managed environment with access to many different tree species of similar age in one location, as well as reducing variation in temperature for trees located in different geographic areas, and inherent control over soil, water, and management conditions.

Fig. 1: The Enea Tree Museum (ETM) in Rapperswil-Jona, Switzerland, RGB image from the drone flight on 11 July 2022. All analysed trees are shown in the map. Inset map shows location within Switzerland.

2 Materials and Methods

The data was collected using a drone-mounted thermal camera to record images of surface temperatures. The thermal images were then mosaicked together to create a georeferenced thermal map of the Enea Tree Museum in °C. Using the thermal mosaics, we delineated the tree crowns, grass, and gravel areas to be analysed and compared. We then extracted the temperature data from all areas and calculated emissivity-corrected temperatures. This data was then used in the analysis (Table 1).

Table 1: Summary of the workflow used in this research



2.1 Data Collection

RGB and thermal infrared images were collected with an agEagle (previously senseFly) Duet-T camera mounted on an agEagle eBee X glider UAV flown over the ETM. The Duet-T camera has an RGB and thermal camera mounted and controlled together so images from both cameras overlap and images can be analysed together.

Flights were chosen for two days in summer 2022 and one day in summer 2023 to get a range of temperatures and conditions. Flights were on 11 July and 18 August 2022, and 16 August 2023. The data collection on 11 July 2022 and 16 August 2023 were mostly sunny days, while 18 August 2022 was mostly cloudy.

All flights were planned in agEagle eMotion software version 3.12 to cover the entire grounds of the ETM within one flight. The flights in 2022 were flown at a height of approximately 61 m on 11 July 2022, 71 m on 18 August 2022, and 61 m in 2023. 555 thermal images were taken on 11 July 2022, 532 on 18 August 2022, and 490 on 16 August 2023 (for more information see Appendix, Table A1). The thermal sensor on the Duet-T requires warming up to get accurate detections, and thus the eBee X flew in a circle for at least 10 minutes after launching to give the sensor ample time to warm up. It was only after these 10 minutes that the eBee X was sent a command to begin its mission and data was collected.

Air temperature, relative humidity, wind speed, and solar radiation were recorded at the same time as the flights at the Eastern Switzerland University of Applied Sciences' Institute of Solar Technology at Rapperswil, approximately 3.6 km from the study site (see Appendix Table A1). Measurements were recorded every 10 seconds and mean values over 30 minutes surrounding the approximate times of the drone flights. Mean air temperature on 11 July 2022 during the flight was 25.2°C and on 18 August 2022 was 22.9°C. The warmest mean temperature was recorded on 16 August 2023 (28.0°C).

2.2 Image Processing

RGB and thermal images were imported into Pix4D Mapper software version 4.9.0 (agEagle) for mosaicking using the template provided by agEagle. RGB and thermal images were co-registered to the same geographic location and stitched together resulting in overlapping mosaics of RGB and thermal images at ground surface distance (GSD) resolutions of 0.03 m in July 2022, 0.05 m in August 2022, and 0.03 m for 2023 (see Appendix, Table A1). While the original GSD were different, we resampled a subset of the imagery and analysed this imagery and found it to have no effect on the results and statistical significance.

2.2.1 Individual Tree Crown Identification in the Imagery

A web map of aerial imagery of the ETM was used by employees of Enea, GmbH to identify the species of individually recognized trees in the images. This served as species validation for the analysis. A total of 192 trees were identified and analysed over the two years.

The locations of the individual trees were imported into ArcGIS Pro (ESRI) and overlaid onto the RGB and thermal image mosaics. A circle polygon layer was created at each location over the most homogeneous thermal area of the sunny side of the tree crown. We chose to focus on homogeneous areas to reduce the influence of shaded areas due to taller sections of trees or neighbouring trees, or due to openings in the trees due to loss of leaves or tree structure. However, in some trees this was not possible due to the highly heterogenous natures of the tree crown temperatures and we used the most similar areas with the least thermal heterogeneity.

2.2.2 Identification of Grassy Lawns, Gravel Paths, and Shaded Areas in the Imagery

Areas covered with managed grassy lawns were similarly designated in ArcGIS Pro by creating circle polygons in large heterogeneous areas of the lawns at the ETM. Similarly, gravel paths, and shaded areas of lawns and gravel paths were identified with circle polygons created in ArcGIS Pro. The lawn, grassy lawn, gravel paths, and shadowed areas were identified for temperature analysis.

2.2.3 Mapping of Thermal Differences

Thermal difference (recorded surface temperature minus mean air temperature) maps were created for each date by subtracting the mean air temperature at the time of the flight from the surface temperature mosaic. This was done for each date (11 July 2022 shown in Figure 2; 18 August 2022 in Appendix, Figure A1; 16 August 2023 in Appendix Figure A2) to visually assess thermal differences.

2.3 Data Analysis

2.3.1 Tree Crown Temperature Analysis

Thermal mosaics and tree crown, grassy lawn, gravel path, and shaded area shapefile polygons were imported into Python 3.8 and temperature values within the circle polygons of the tree crowns were extracted. Data was organized using the 'pandas' Python library for statistical analysis.

We corrected the recorded temperatures based on surface type emissivity by using the Stefan-Boltzmann correction equation (Eq. 1):

$$T_{surface} = \sqrt[4]{\frac{{T_{sensor}}^4 - (1 - \varepsilon) * {T_{air}}^4}{\varepsilon}} \quad (1)$$

Where $T_{surface}$ is the corrected temperature at the surface, T_{sensor} is the corrected measured temperature from the thermal camera, T_{air} is the mean ambient air temperature during the flight, and ε is the emissivity of the surface. Temperatures were converted to Kelvin before

the calculation and back to Celsius after the calculation. The extracted pixel values from the circle polygons were emissivity-corrected based on surface type emissivity, using $\varepsilon = 0.98$ for tree crowns and grass, and $\varepsilon = 0.92$ for the gravel path. A literature review found vegetation emissivity ranges of about 0.95-0.99 and choose 0.98 as a common value for all vegetation in the study. We used $\varepsilon = 0.92$ for the gravel path as this is a conservative value for rough stone. The mean surface temperature of each polygon was then calculated based on the emissivity-corrected values.

Mean air temperatures for the flight time were subtracted from median individual emissivity-corrected tree crown temperatures (tree crown temperatures from this point forward) and compared across species. The results indicate how the tree crown temperatures compared to air temperature, with negative values indicating tree crown temperatures below air temperature, positive values indicating tree crown temperatures above air temperature, and zero indicating the same temperature. Analysis was done on all tree species with eight or more individual trees identified in the ETM to reduce the effects of inter-tree variation. This resulted in eight tree species (see Appendix, Table A2) being compared in the final analysis. Box plots were created for the temperature differences for each species and each date. We tested if temperature differences were significantly different between species using a Kruskal-Wallis H-test to determine if there was at least one significant difference per date. We followed this with Dunn's post-hoc test, using a Holm-Bonferroni correction, for pairwise comparisons to identify the significant differences between species. We used the non-parametric tests since the thermal sensor data is not normally distributed.

2.3.2 Open Grass, Gravel Path, and Shaded Area Temperature Analysis

Mean air temperatures for the flight time were subtracted from median grassy lawn, gravel path, and shaded area circle polygons identified in the imagery. The results indicate how the different surface temperatures compared to air temperature, with negative values indicating surface temperatures below air temperature, positive values indicating surface temperatures above air temperature, and zero indicating the same temperature. Box plots were calculated for the temperature distribution of the surfaces and each date. Median temperature differences were considered significantly different between surface types by using a Kruskal-Wallis H-test to determine if there was at least one significant difference per date. We followed this with Dunn's post-hoc test, using a Holm-Bonferroni correction, for pairwise comparisons to identify the significant differences between surfaces. We used the non-parametric tests since the thermal sensor data is not normally distributed. The boxplot also included a category for the median value of the difference with air temperature for a combined tree species group, that included all trees in the study (not just those with more than eight individuals) to highlight the differences in surface temperatures.

2.3.3 Factors Influencing Temperature Differences

Previous studies have indicated the influence of specific leaf area (SLA), leaf area index (LAI), and leaf area density (LAD) on tree drought resistance (e. g. SAKSCHEWSKI et al. 2016) cooling effects (ARMSON et al. 2013, RAHMAN et al. 2015, HELLETSGRUBER et al. 2020). We chose to investigate whether specific leaf area (SLA) is correlated with surface temperature differences in our study species. Specific leaf area is the density of a leaf, measured as the area of a leaf divided by its dry weight. We used a literature review to determine SLA (Appendix 1, Table A1) for all species besides *Parrotia persica*, for which we could not find any

published information on SLA. We, therefore, took five leaves each from two trees at the OST campus in Rapperswil in August 2024 and within the first 10 minutes of clipping them from the tree, scanned the leaves to a jpeg and dried them in a drying oven (80°C for 24 hours). We imported the jpeg images in the R statistical program (R CORE TEAM 2025) and calculated the leaf area using the 'LeafArea' package (KATABUCHI 2015). We weighed the dried leaves and calculated the mean SLA for each leaf by dividing the area by the weight for each leaf.

We then examined the influence of SLA on the temperature differences (tree-crown mean temperature minus air temperature). We used a linear mixed-effects (LME) model in Python using 'pandas' and 'statsmodels' packages with temperature differences as the dependent variable and SLA and date as fixed effects and included their interactions. SLA was mean-centered to help interpretability, since SLA cannot equal zero. We used LME because we had multiple temperature difference measures across three dates from the same individual trees, and this model accounts for non-independence of observations within the same tree. We did not include species and individual tree in the fixed effect to avoid problems with collinearity, since SLA is the same per species and thus across dates for each individual tree. We included individual tree as a random effect, allowing each tree to have its own baseline temperature difference. Model parameters were estimated using Restricted Maximum Likelihood, and significance of the fixed effects were determined using Wald z-tests.

3 Results

3.1 Species Comparisons of Tree-crown Temperatures

The coolest day of the study was 18 August 2022 with a mean air temperature of 22.9°C and all median tree crown temperatures being below air temperature. The warmest day, 16 August 2023 (mean air temperature of 28°C), found all median tree crown temperatures to be above the air temperature except *Platanus* x *hispanica*. The third day of the study, 11 July 2022, had a mean air temperature near the mid-point between the two other days (25.2°C), but still found most tree species to have median tree-crown temperatures below air temperature. Maps of the thermal differences of surface temperature from the ambient air temperature for all dates (Figure 1, Appendix Figures A1, A2) highlight the impacts of the cooler tree crowns and shaded areas (blue areas). These also show that open grass had a mean of 6.6°C warmer than air temperature over the three measurement dates (red areas).

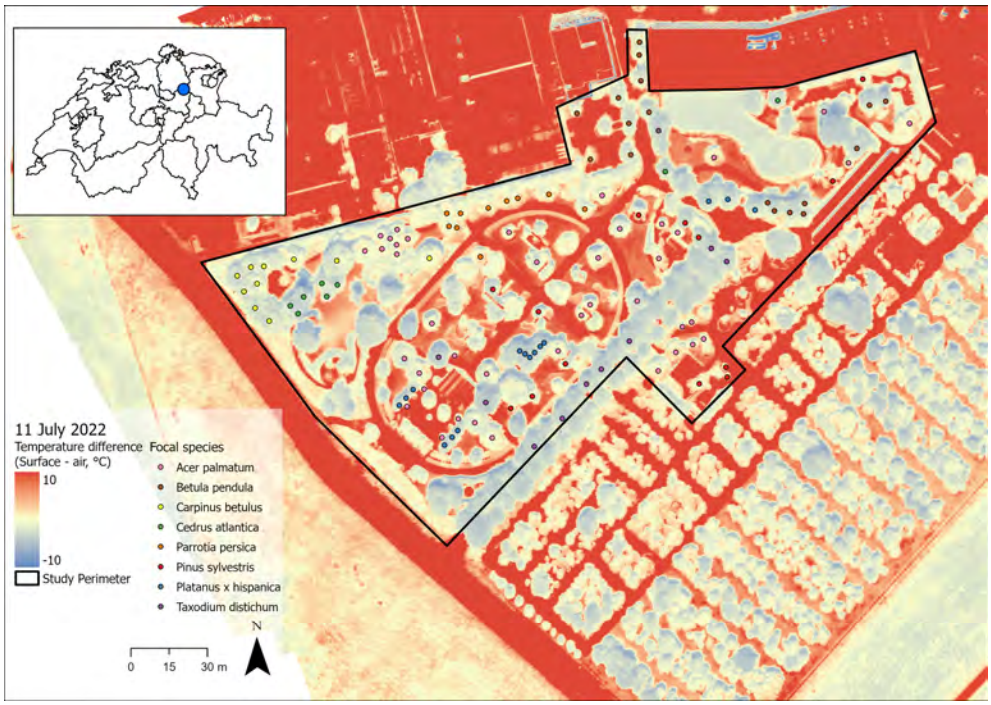


Fig. 2: Surface temperature differences with ambient air temperature on 11 July 2022, which was sunny and warm, but had the second-warmest air temperature of the three study dates. Values above zero (towards red) indicate warmer surface temperatures than air temperature, while values below zero (towards blue) indicate cooler surface temperatures than air temperature.

All tree species were found to have cooler median tree canopy temperatures than the air temperature in August 2022, while all but two had cooler median tree canopy temperatures in July 2022 (Figure 3). All but one tree species were found to have warmer median tree canopy temperatures than the air temperature in August 2023, although two others had difference values very close to zero. The tree crown temperature of *Platanus* x *hispanica* (the London plane, a frequently used species in urban greening) was below the mean air temperature for all dates (Figure 3). This was the only species that was found to be cooler than air temperature for all dates. *Taxodium distichum* (Bald Cypress) had the lowest median species temperature difference for both dates in 2022. *Cedrus atlantica* (Atlas Cedar) also consistently had lower temperature differences than most other species.

In contrast, *Parrotia persica* (Persian Ironwood) had the highest median temperature difference with air temperature for all dates and was one of only two species with higher temperatures than air temperature in July 2022 (Figure 3). *Acer palmatum* (Japanese Maple) had the second highest median temperature difference across all dates.

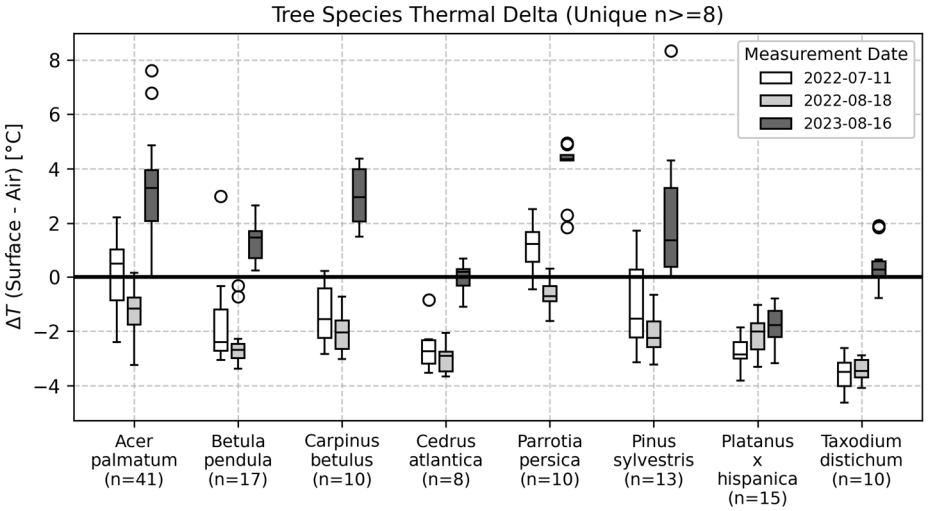


Fig. 3: Boxplot showing differences in temperatures between tree-crown surfaces and air temperature from species with more than eight individuals for all three study dates. Values above zero indicate warmer surface temperatures than air temperature, while values below zero indicate cooler surface temperatures than air temperature.

Species identity had a significant effect on temperature differences for all dates: 11 July 2022, $H(7) = 77.44$, $p<0.001$; 18 August 2022, $H(7) = 62.92$, $p<0.001$; 16 August 2023, $H(7) = 83.24$, $p<0.001$. Post-hoc Dunn's test with Bonferroni correction found both *Parrotia persica* and *Acer palmatum* warmer than *Betula pendula*, *Cedrus atlantica*, *Platanus* x *hispanica*, and *Taxodium distichum* for all dates (Appendix, Tables A4-A6).

3.2 Open Grass, Gravel Path, and Shaded Area Temperature Analysis

The gravel paths always had the largest difference with air temperature and were thus the warmest surfaces, while the open grass areas consistently had the second highest temperature differences (Figure 4). The median gravel path surface temperature was more than 18 °C warmer than air temperature on the two warmest days of the study and was still more than 6°C warmer on the coolest day with the most clouds (Figure 4). In contrast, shaded grass had mean temperatures below air temperature on the two sunny days, but not on the cloudy day, while tree crowns were cooler than air temperature except on the hottest day. Open grass and gravel had the warmest mean temperature differences. The mean shaded grass temperature difference across all three dates were 2.9°C cooler than the air, 2.3°C cooler than the tree crowns, 2.7°C cooler than the shaded gravel, 9.5°C cooler than open grass, and 17.8°C cooler than open, gravel paths. In contrast, the shaded gravel was on average 0.2°C cooler than air temperature across all three dates.

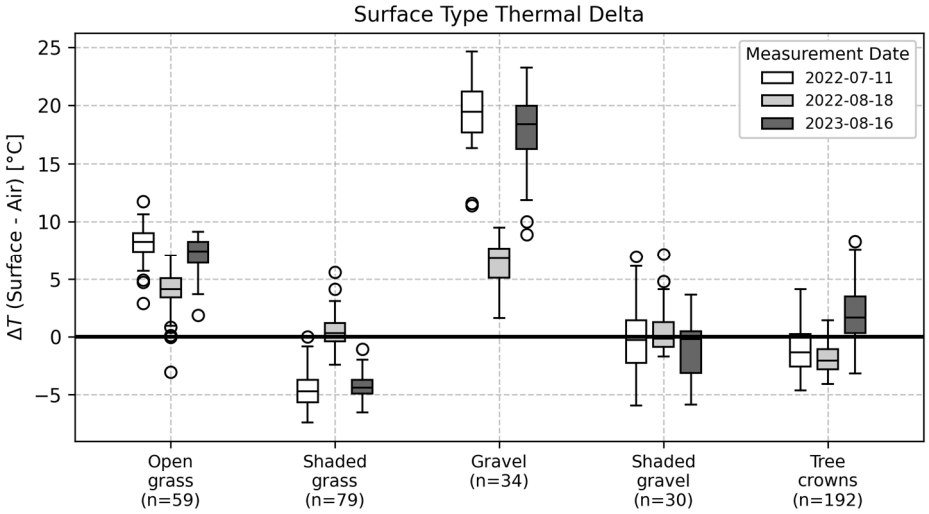


Fig. 4: Boxplot showing differences in temperatures between different surface types and air temperature for all three study dates. Values above zero indicate warmer surface temperatures than air temperature, while values below zero indicate cooler surface temperatures than air temperature.

Surfaces types had a significant effect on temperature differences for all dates: 11 July 2022, $H(4) = 290.55$, $p<0.001$; 18 August 2022, $H(4) = 280.41$, $p<0.001$; 16 August 2023, $H(4) = 316.68$, $p<0.001$. Post-hoc Dunn's test with Holm-Bonferroni correction found no difference in temperature differences between open grass and gravel paths for all dates except August 2023, which was the hottest day, (Appendix, Tables A7-A9) despite the large differences in temperature differences. The Dunn's test is based on distribution of ranks instead of means, and high variance of the gravel measurements, with low sample size, may have led to overlaps in the rank-sum distributions with open grass, thus not identifying a significant difference. Shaded grass was cooler than all other surfaces for all dates, except in August 2022 for shaded gravel, where there was no difference, and being warmer than tree crowns.

3.3 Factors Influencing Temperature Differences

Linear mixed-effects modelling found SLA significantly influenced the temperature difference between mean tree-crown temperature and air temperature, but the strength of interactions varied significantly across dates, with the warmest day (16 August 2023) having the strongest relationship and the coolest day (18 August 2022) having the weakest relationship compared to 11 July 2022 (Appendix, Table A3). Higher SLA values were significantly correlated with slightly higher tree-crown temperatures than air temperature (Figure 5).

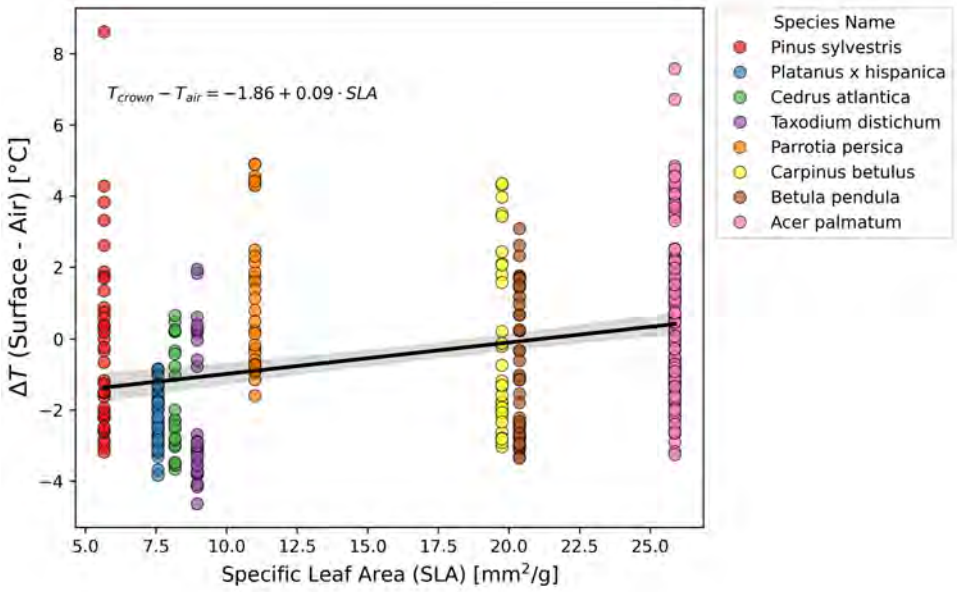


Fig. 5: Linear regression line showing relationship between raw SLA values and temperature differences for all dates for each tree (LME: $\beta = 0.09$, $p < 0.001$). Each point represents an independent tree measurement. Measurements were taken on 11 July and 18 August 2022, and 16 August 2023.

4 Discussion

The effects of climate change are increasingly being seen all over the world, leading urban planners and landscape architects to identify ways to reduce the effects on everyday life. This is especially the case in cities, where increased temperatures experienced as the urban heat island effect are causing problems including increased elderly deaths, uncomfortable temperatures, increased electricity use for cooling, etc. (FEIßEL et al. 2018, SMID et al. 2019, IUNGMAN et al. 2023). While it is known that vegetation, especially tree cover with its shading and evaporative cooling effect helps reducing these overheating effects, little work has investigated how individual tree species can influence microclimate cooling.

This study used drone-collected thermal imagery to analyse surface temperatures of eight different tree species frequently used in landscape architecture, as well as different urban surfaces such as lawns and gravel paths to understand how they differed from air temperatures in summer in a managed park (ETM) in northeastern Switzerland. Significantly, we found two species whose tree-crown temperatures were consistently the warmest compared to ambient air temperature, and three species that were consistently the coolest compared to ambient air temperature. *Parrotia persica* and *Acer palmatum* consistently had warmer temperatures than air temperature, and warmer crown temperatures than the other species. Alternatively, the tree-crown temperature of *Platanus x hispanica* was found to be lower than the air temperature for all three dates. Two other trees, *Taxodium distichum* and *Cedrus atlantica*, consistently showed lower tree crown temperatures than the other trees in the study. As ex-

pected, we found shaded areas to be cooler than non-shaded grassy areas on sunny days, but also noted cooler tree-crown temperatures on the cloudy day. This study identified consistent differences in tree-crown surface temperature with air temperature across eight different tree species commonly used in landscape architecture projects in Switzerland across different summer weather conditions. This suggests that proper species choices for urban tree planting may help promote cooling.

The data was collected at three different points in time and represents three different weather conditions. We found that SLA and date, as well as interactions between SLA and date, significantly contributed to explaining variation in temperature difference. A higher SLA – hence thinner leaves, i.e. less biomass per leaf area – was significantly correlated with higher tree crown temperatures than air temperature. The thinner and less drought resistant leaves of tree species with a higher SLA might heat up faster and may have closed their stomata earlier during midday heat due to water stress than trees with leaves with a lower SLA. However, precise stomatal conductance measurements are needed to understand the functional mechanisms leading to differences in leave surface temperatures associated with SLA. Our results are consistent with research observing that thicker leaves with higher water content and high stomatal conductance were more effective at cooling than thinner leaves (ARNOLD et al. 2025, ZHANG et al. 2025). These SLA results suggest that we can use knowledge of leaf morphology for green infrastructure design and help inform planners to consider different leaf morphologies with the goal of creating cooler microclimates. However, additional tree properties also play a role in the temperature differences suggesting that more research is needed to determine the effects of tree properties such as age, height, crown diameter, and trunk diameter at breast height as well as wood anatomy (e. g. ring-porous wood vs. coniferous wood with different tracheid diameters). Hence, more extensive studies can help city planners identify suitable tree species and combinations of tree species (e. g. a combination of fast-growing trees with thinner leaves with a high SLA and tree species investing in longer lasting leaves with a lower SLA) to optimise tree community cooling at different times of the day to reduce impacts of UHI, especially in climates where predicted temperature and rainfall changes could affect long-term survival of traditionally used species.

These inter-species differences in the tree-crown surface temperatures suggest that planting of some species could help reduce the temperature differences seen in urban heat islands more than others, and that future planners could concentrate on using some species over others to help promote localized cooling of microclimate in cities and settlements. Importantly, soil quality and surface covers also influence the urban microclimate. Our analyses showed that the mean shaded gravel temperature was only about 0.2°C cooler than air temperature across all three dates. However, trees planted in urban contexts are often surrounded by gravel, which helps reduce maintenance costs and may have some biodiversity effects for ruderal species. Our findings suggest that the overall effect of gravel shade on cooling is not much, as the shaded areas were almost the same temperature as the air. This does not take physiological equivalent temperature into account, and surely it is cooler in the shade than in the open sun on a hot day, but it is interesting to note that preferring gravel may not have overall cooling effects (especially in comparison with shaded lawns that were 2.7°C cooler than air temperature and 16.1°C cooler than gravel). These findings are consistent with previous research (ZITER et al. 2019) suggesting that removing sealed surfaces has the greatest effects on cooling in cities.

This project focused on observing the tree-crown temperature differences between species, while other studies have investigated the effects of morphological, and locational differences in tree cooling (RAHMAN et al. 2015, RAHMAN et al. 2019, HELLETSGRUBER et al. 2020). While tree-crown temperature readings based on thermal images are not directly comparable to air temperature readings around the tree, CHEUNG et al. (2021) found drone-based thermal images were highly and significantly correlated with below-canopy surface temperature and below-canopy air temperature. Similar to our study, HELLETSGRUBER et al. (2020) found *Platanus* x *hispanica* to have high cooling potential due to having the largest mean difference with reference wet bulb globe-temperature (−4.72 ± 0.40 °C), and air temperature at 1.1 m (−5.70 ± 1.03 °C) across multiple European cities. Our study suggests the drone-based tree-crown temperature method might be suitable for identifying which trees offer the most cooling in summer.

This study aimed to determine if drone-based thermal images could identify consistent species differences in tree-crown temperatures compared to ambient temperature on days with different weather conditions. An advantage of using a drone to record thermal images at arboreta such as the Enea Tree Museum is collecting many recordings all at once. While further studies need to be done to validate the correlation of drone thermal measures and human comfort, this method could lead to more efficient data collection over large areas in a relatively short amount of time, offering substantial benefits for spatial planners seeking to compare the cooling effects of different tree species planted under varying planting contexts (e. g., along roads, in parks, in residential areas) on the same day at similar times (BARTESAGHI-KOC et al. 2021).

Data collection from drones can be relatively quick compared to collecting individual tree measures. Results from this study are similar to other, more detailed studies in terms of species temperature differences with air temperature, suggesting this method could be more efficient in terms of data collection. More studies in different locations and at different times of day will be needed to verify these findings, as well as to collect tree-based air temperature recordings and investigate other impacts on cooling including leaf area index and diameter at breast height. This may be difficult in practice due to management and environmental differences in trees planted in different locations. The ETM provided a controlled environment with the same environmental and management conditions for all trees, thus reducing the number of outside variables that could potentially lead to differences seen between study locations. Future longer-term research will revolve around monitoring year-round air temperature and humidity below the tree crown to determine if the temperature differences between species hold true. Future drone flights using thermal imagery can also help determine the correlation between tree crown temperature and below tree crown air temperatures. Additionally, flying the drone at different times of the day will increase understanding of how tree crown temperatures change through the day. It will also be important to see how air temperature and tree crown temperature are correlated in the evenings to help understand how tree crowns retain heat.

The information gained from this, and future studies can be incorporated into tree selection tools for cities and settlements in similar climate regimes as Rapperswil-Jona. Tools like Citree (https://citree.de, VOGT et al. 2017) can incorporate thermal information to help planners consider cooling when choosing which trees to plant. Incorporating thermal information into emerging planning schemes like the “sponge city” we can further improve the way cities aim to tackle UHI effects, drought, flooding and other impacts of climate change. It will be

important to choose the right tree species and combination of tree species for each climate and location (MORAKINYO et al. 2020). It is also important to consider biodiversity and water use, as these factors can support landscape architects in planning for increasingly variable climate conditions and in preparing for a range of future scenarios. This is particularly relevant in regions where more frequent droughts may limit water availability, even for tree species that provide strong cooling effects.

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Appendix

Table A1: Meteorological mean values and flight information for the three drone flight dates. Meteorological data from the Eastern Switzerland University of Applied Sciences' Institute of Solar Technology at Rapperswil, approximately 3.6 km from the study site.

Date	Mean flight time of day	Flight height (m)	Mosiac pixel resolution (m)	Mean air temperature (°C)	Mean relative humidity (%)	Mean wind speed (m/s)	Mean intensity of solar radiation (W/m²)
11 July 2022	12:45	61	0.03	25.2	31.0	1.9	942.0
18 August 2022	11:24	71	0.05	22.9	55.0	1.6	545.1
16 August 2023	11:14	61	0.03	28.0	41.6	1.7	797.0

Table A2: Properties of trees analysed. Data on Specific leaf area (SLA) were collected to analyse their correltation with the temperature differences between tree-crown temperature and air temperature. (n) values shown for the different species analysed.

Species (n)	Origin	Taxonomic classification	Life-form	Specific leaf area [mm²/mg]	Wood anatomy	Winter Hardiness Zone	Habitat
Acer palmatum Thunb. (41)	Japan, Taiwan, China	Angiosperms, Sapindaceae	deciduous	25.87[1]	Diffuse porous	6b	Cool and moist mountain forests, sun tolerating
Betula pendula Roth (17)	Europe, North Africa, Caucasus, Middle East, Western Siberia	Angiosperms, Betulaceae	deciduous	20.38[1]	Diffuse porous	2	Pioneer species on nutrient poor, dry or wet soils
Carpinus betulus L. (10)	Europe, Caucasus, Middle East	Angiosperms, Betulaceae	deciduous	19.75[1]	Diffuse porous	5b	Mixed deciduous forests on moderately dry to fresh soils
Cedrus atlantica (Endl.) Manetti ex. Carrière (8)	Algeria, Morocco	Gymnosperms, Pinaceae	evergreen	8.17[1,2]	Coniferous wood, small tracheids	7a	Forests in the Atlas mountains, mesic soils with short droughts

Table A2 (continued)

Species (n)	Origin	Taxonomic classification	Life-form	Specific leaf area [mm²/mg]	Wood anatomy	Winter Hardiness Zone	Habitat
Parrotia persica C. A. Mey. Persian Ironwood (10)	Northern Iran	Angiosperms, Hamamelidaceae	deciduous	11.0[1]	Diffuse porous	6a	Hyrcanian forests. Alluvial mesic forests with periodic flooding and coastal plains of the Caspian Sea, thermophilic, sun loving, fire resistant
Pinus sylvestris L. (13)	Europe, Central Asia, Caucasus, Middle East	Gymnosperms, Pinaceae	evergreen	5.66[1]	Coniferous wood	1	Pioneer species on nutrient poor, dry to wet soils, thermophilic
Platanus x hispanica Münchh. (15)	–	Angiosperms, Platanaceae	deciduous	7.57[3]	Diffuse to semi-ring porous	6b	Alluvial forests, well drained, consistently moist soils, thermophilic
Taxodium distichum (L.) Rich. (10)	North-Eastern USA to Central America	Gymnosperms, Cupressaceae	evergreen	8.96[1]	Coniferous wood, large tracheids	6b	Coastal Plains on saturated and seasonally inundated soils, alluvial forests, thermophilic

Nomenclature follows WFO (2025): World Flora Online; www.worldfloraonline.org (accessed on: 23 Jul 2025). Life form and Habitat according to ROLOFF & BÄRTELS 2018, JOSHI et al. 2024, FloraVeg.EU – Database of European Vegetation, Habitats and Flora. www.floraveg.eu.

SLA values were mainly obtained from published values listed in the Try database (KATTGE et al. 2020[1]), as well as data from LARA-ROMERO et al. 2022[2] and HAMBUCKERS et al. 2022[3]. Data on wood anatomy were obtained from www.wood-database.com/wood-filter/ (accessed on: 23 Jul 2025) and SCHOCH et al. 2004 www.woodanatomy.ch (accessed on: 23 Jul 2025).

Table A3: Results of mixed-effect model examining different effects on temperature differences between crown temperature and air temperature

Predictor	Coefficient (β)	Std. Error	z-value	p-value	95% CI
Fixed Effects					
Intercept	-1.071	0.14	-7.63	< 0.001	[-1.35, -0.80]
Date (Aug 16, 2023)	2.889	0.131	22.05	< 0.001	[2.63, 3.15]
Date (Aug 18, 2022)	-0.875	0.131	-6.68	< 0.001	[-1.13, -0.62]
SLA (centered)	**0.094**	**0.017**	**5.44**	**< 0.001**	**[0.06, 0.13]**
Date (Aug 16, 2023):SLA	0.034	0.016	2.09	0.036	[0.00, 0.07]
Date (Aug 18, 2022):SLA	-0.052	0.016	-3.21	0.001	[-0.08, -0.02]
Random Effects					
Tree ID (Variance)	1.377	0.263	–	–	–

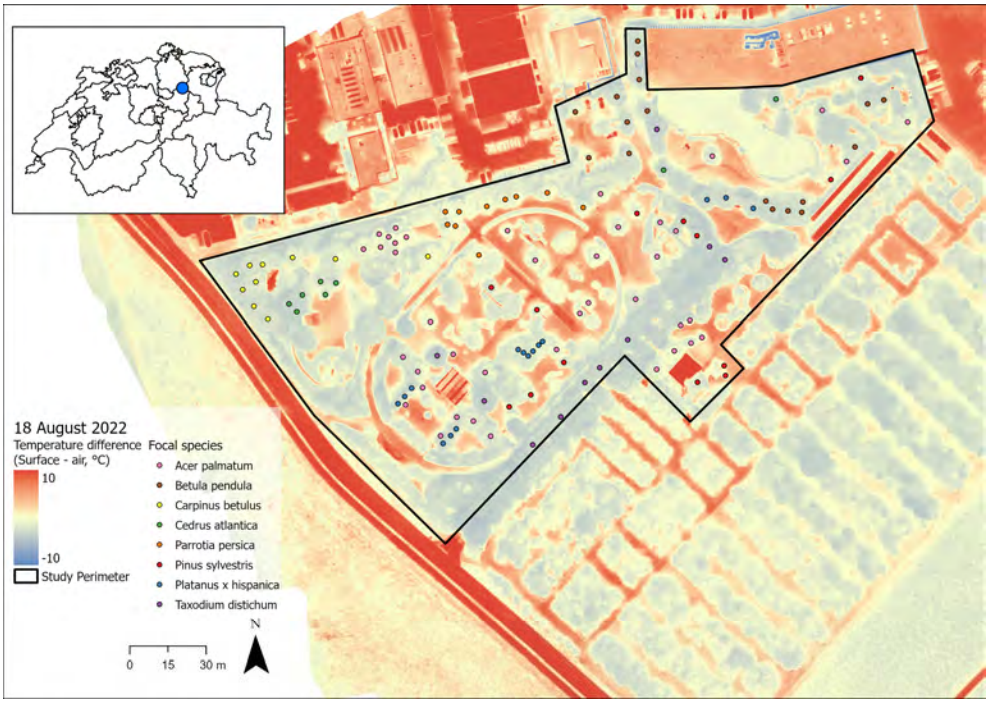

Fig. A1: Surface temperature differences with ambient air temperature on 18 August 2022, which was the cloudiest and coolest day of the study. Values above zero (towards red) indicate warmer surface temperatures than air temperature, while values below zero (towards blue) indicate cooler surface temperatures than air temperature.

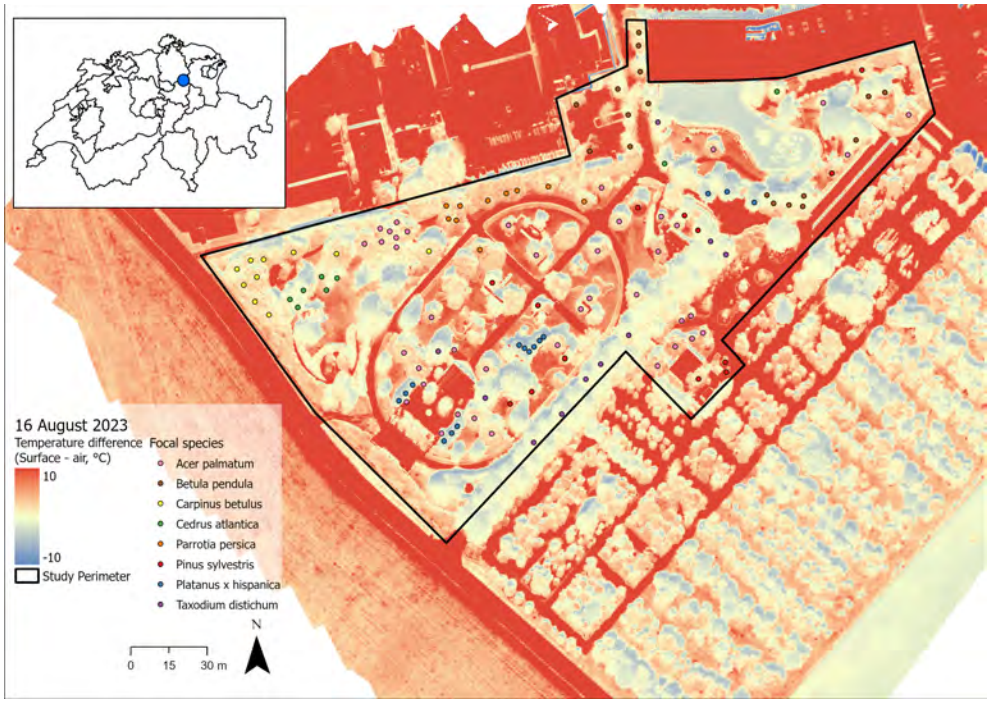

Fig. A2: Surface temperature differences with ambient air temperature on 16 August 2023, which was the sunniest and warmest day of the study. Values above zero (towards red) indicate warmer surface temperatures than air temperature, while values below zero (towards blue) indicate cooler surface temperatures than air temperature.

A Simulation-Based Approach to Climate-Resilient Rural Landscape Planning: A Case Study on Thermal Environment Optimization

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Abstract: Climate change is intensifying extreme heat risk in rural areas, yet planning-oriented quantitative evidence remains limited. Using a representative Linpan settlement on the Western Sichuan Plain, China, this study builds a scenario matrix by varying the area shares of five elements – paving, tree vegetation, water bodies, buildings, and farmland – and applies ENVI-met to simulate a typical hot day and extract key microclimate and comfort metrics. Results show that trees and water create stable cool patches, while courtyard cores remain largely stable across scenarios; comfort gains are driven mainly by tree shading, and more contiguous vegetation yields more continuous relief. Machine-learning attribution further indicates that air temperature is more sensitive to paving, building, and farmland shares, wind speed is controlled primarily by building enclosure, and MRT/PMV are strongly governed by vegetation shading; simultaneous increases in buildings and paving amplify thermal discomfort. These findings translate into climate-adaptive rural landscape planning strategies and a reusable evaluation framework.

Keywords: Rural landscape planning, climate adaptation, thermal environment, ENVI-met, nature-based solutions

1 Introduction

Extreme heat risk under climate change has become a critical issue affecting human settlements and spatial planning. Compared with urban areas, rural regions exhibit substantial differences in spatial form, land- use structure, and modes of production and daily life, yet their thermal environmental responses and adaptation pathways remain insufficiently studied in a systematic manner (DU et al. 2024). In rural areas dominated by agriculture and natural resources, changes in landscape structure often have a direct impact on local microclimatic conditions and residents' outdoor heat exposure (GAO et al. 2023, HAN et al. 2023, VAN DER VLIST 1998).

Although microclimate regulation principles – such as vegetation shading, evaporative cooling from water bodies, surface albedo, and spatial ventilation – have been discussed for decades and are broadly accepted, the key challenge in rural planning practice lies in selecting feasible spatial adjustment pathways under policy and land-use constraints. In the ongoing process of rural development and renewal, land-use adjustments, increased construction intensity, and the reorganization of landscape elements are reshaping the thermal characteristics of traditional rural spaces (ARAM et al. 2019, LIPPER & CAVATASSI 2024). However, planning decisions in practice are still largely based on empirical judgment, with limited quantitative evaluation of the thermal effects of different landscape configurations under extreme heat conditions. This constrains the development of climate-adaptive spatial optimization strategies. How to enhance the thermal resilience of rural environments through rational

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landscape configuration under existing land-use policies and ecological constraints remains a key issue requiring further investigation (McKenzie et al. 2011).

Landscape planning at the rural scale has considerable potential for microclimate regulation, yet existing studies have mostly focused on single elements or qualitative discussions, with relatively few systematic comparisons of thermal environmental responses under different planning scenarios that integrate multiple landscape elements. In particular, under extreme heat conditions, the nonlinear interactions and synergistic mechanisms among different elements have not been fully explored (Tümtürk et al. 2024).

Against this background, this study employs digital microclimate simulation to quantitatively evaluate the thermal effects of different rural landscape planning schemes. It aims to clarify the regulatory mechanisms of key elements – vegetation, water bodies, buildings, pavement and farmland – under varying proportions and combinations, thereby providing scientific evidence for climate – adaptive rural planning. The study focuses on the following research questions:

(1) Scenario differences and overall patterns: How does the spatial pattern of the rural thermal environment change across planning scenarios, and which areas and landscape elements primarily drive these differences? (2) Sensitivity and effective ranges of individual elements: How do changes in pavement, farmland, vegetation, water bodies, and building proportions affect the magnitude and diurnal dynamics of thermal indicators, and how do their effective spatial ranges and impact boundaries differ? (3) Multi-element interactions and planning translation: Do combined landscape elements exhibit synergistic or inhibitory effects, and how can these patterns be translated into climate-adaptive planning principles for scenario selection and design?

2 Methodology

2.1 Study Area

This study focuses on Linpan, a representative example of the traditional rural settlement form on the Western Sichuan Plain in southwest China. At a small spatial scale, Linpan integrates vegetation, waterways, farmland, and residential buildings into a compact and hybrid landscape unit with strong microclimate-regulation potential (Figure 1). In recent years, peri-urbanization has driven pressures such as construction expansion, fragmentation of farmland and vegetation, increased hard paving, and reduced water bodies, which may undermine its thermal adaptability and elevate heat risk.

The study site is Taojia Courtyard, a typical Linpan building cluster in the peri-urban rural area of Chengdu, Sichuan Province (103.97°E, 30.33°N). The area is flat with favorable irrigation conditions, dominated by protected farmland, and features an intact Linpan structure with moderate scale and complete elements, providing strong representativeness and suitability for simulation (Figure 1).

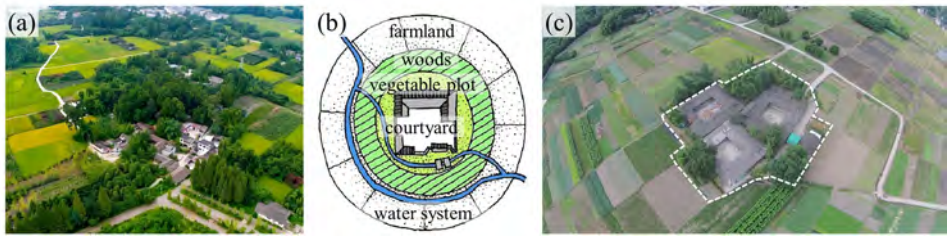

Fig. 1: Spatial prototype and component composition of the Linpan settlement: (a) Typical Linpan settlement, (b) Abstracted form of the Linpan settlement, (c) Case study used in this research

2.2 Planning Scenarios

Although land-use change is constrained by policies such as permanent farmland protection, low-intervention, implementable pathways can still be explored by optimizing the areal shares and spatial configurations of vegetation, water bodies, buildings, paving, and farmland. We constructed a scenario matrix using landscape-element area ratios as key variables: S0 is the baseline, and S1-S4 prioritize adjustments in paving (land-surface pattern), vegetation, water, and building ratios, respectively (Figure 2). Scenarios incorporate typical element coupling (e. g., building growth usually entails more paving, and new water features may replace some farmland), with any farmland adjustment limited to existing cultivated land and kept within protection requirements. Cross-scenario comparisons quantify the thermal effects of individual elements and their combinations to support climate-adaptive option selection.

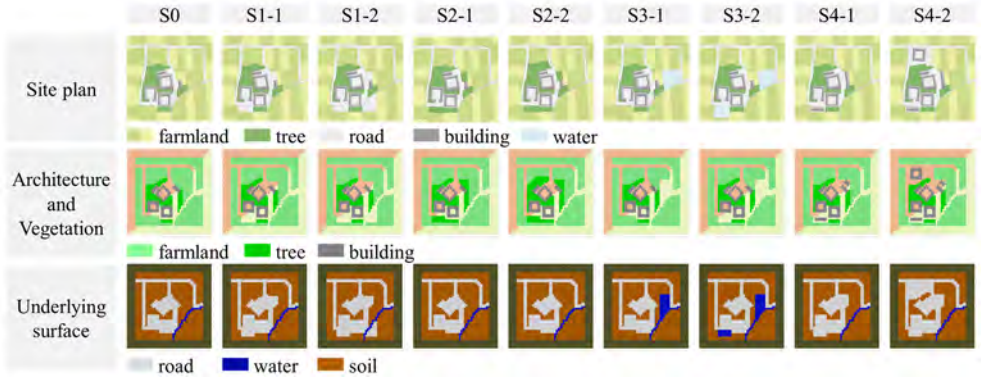

Fig. 2: Planning scenario construction and ENVI-met model setup

2.3 Software Simulation

This study uses the ENVI-met 3D CFD model to simulate rural microclimate under alternative planning scenarios. ENVI-met couples vegetation, surface materials, building morphology, and meteorological forcing to produce high-resolution near-ground microclimate and thermal-comfort estimates (PINTO-CORREIA & KRISTENSEN 2013, SIMON et al. 2018).

June 22, 2024 was selected as the forcing day. Boundary conditions were derived from the nearest weather station, and the ranges of key meteorological variables (AT, RH, WS) are reported in Table 1 to document within-day variability. Model performance was assessed by comparing hourly measured air temperature from three representative courtyards with the corresponding S0 outputs.

Terrain elevation was obtained from field surveying; buildings and paved surfaces (including roads) were extracted from UAV imagery and corrected by site checks; surface types were classified from field investigation. The domain was extended by five nesting grid cells to reduce boundary effects. Simulations ran for 25 h from 00:00 on June 22, covering a full diurnal cycle. Outputs included air temperature (AT), wind speed (WS), and mean radiant temperature (MRT), with thermal comfort evaluated using PMV.

Table 1: Key meteorological ranges for the simulation day

	Air temperature (℃)	Relative humidity (%)	Wind speed (m/s)
Maximum	29	94	1.7
Minimum	22	52	0
Average	25.17	73.17	0.75

2.4 Characteristic Points

To support quantitative cross-scenario comparison, six characteristic points were used for hourly extraction. A-C are courtyard centers representing primary activity spaces, while D-F are located in areas with the largest scenario-induced changes to capture local microclimate and comfort responses (Figure 3). Together, they represent surrounding small-scale conditions and enable time-series comparison and key-difference identification.

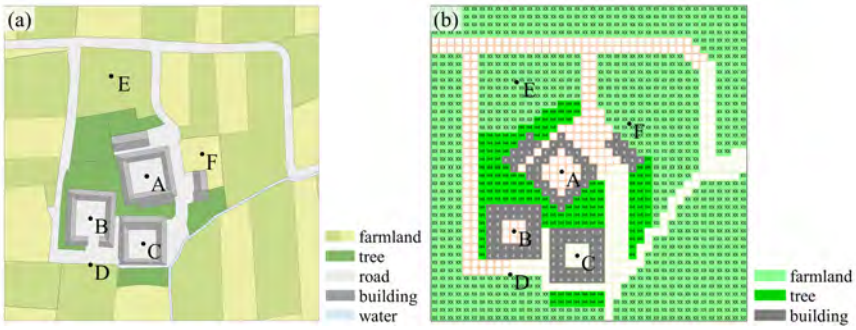

Fig. 3: Distribution of characteristic points and monitoring locations: (a) Plan view, (b) Simulation model

3 Results and Discussion

3.1 Validation

We tested site applicability and parameter settings by measuring hourly air temperature in three representative courtyards on 22 June 2024 and comparing the records with ENVI-et outputs at the corresponding S0 feature points. Agreement was evaluated using R^2, Pearson's r, and MAPE (Middel et al., 2014; Simon et al., 2018). As shown in Table 2, the three points achieved $R^2 = 0.971–0.975$, $r = 0.985–0.988$, and MAPE ≈ 2%, indicating that the model reproduces the diurnal temperature pattern of this typical hot day.

This comparison serves as a site-specific consistency and parameter-check for subsequent relative scenario comparisons under identical boundary conditions, rather than a comprehensive field validation of absolute thermal comfort.

Table 2: Validation results comparing measured and simulated air temperature.

Location	Courtyard 1	Courtyard 2	Courtyard 3
R^2	0.974	0.971	0.975
Pearson	0.987	0.985	0.988
MAPE	2.05%	1.94%	2.39%

3.2 Overall Differences in the Rural Thermal Environment under Different Planning Scenarios

As shown in Figure 4, scenarios produce distinct summer heat patterns: trees and water generate stable local cool patches, while paving and building changes have weaker, mostly near-field effects. Courtyard temperatures remain largely stable, indicating Linpan-scale thermal buffering. Tree belts around dwellings form continuous cool corridors, whereas open farmland warms rapidly into hot spots, underscoring the cooling value of the "vegetation-dwelling" configuration.

PMV patterns broadly follow air temperature but with stronger contrasts. Low-PMV zones align mainly with tree vegetation, and clustered trees near buildings sustain better comfort during peak heat; farmland remains largely uncomfortable. Vegetation also shows a contiguous/synergistic effect, producing more continuous comfort relief even when patchy (ARAM et al. 2019), whereas water-body benefits are more localized and point-like. Overall, scenario differences are driven primarily by vegetation and water configurations, with buildings and paving playing secondary roles-supporting priority protection and enhancement of tree-centered Linpan structure in rural renewal.

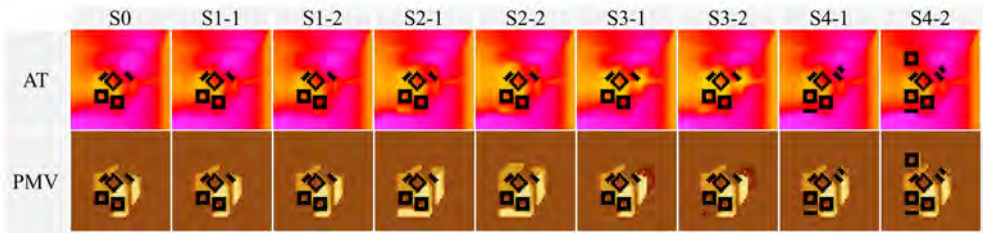

Fig. 4: Near-ground AT and PMV at the hottest time under different planning scenarios

3.3 Key Factors and Element Importance Identified by Machine Learning

3.3.1 Differences in Key Drivers across Thermal Indicators

Random-forest feature importance indicates that the controlling elements differ by indicator (Figure 5). For air temperature (AT), paving, buildings, and farmland show relatively high importance, while water bodies contribute the least, suggesting AT is more responsive to surface and built proportions at this scale. Wind speed (WS) shows a highly concentrated pattern, with building proportion dominating, highlighting spatial enclosure as the primary driver of local ventilation; other elements play minor roles. In contrast, vegetation clearly dominates mean radiant temperature (MRT) and PMV, far exceeding other elements and emphasizing the role of shading and radiation reduction. PMV closely mirrors MRT, with vegetation most important, followed by paving and buildings, and water contributing relatively little. Overall, AT is more influenced by surface/built shares, whereas radiation conditions and thermal comfort are largely vegetation-driven.

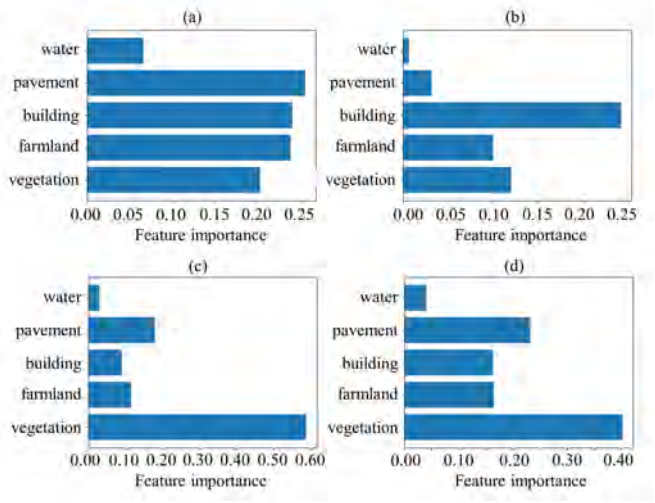

Fig. 5: Feature importance of landscape elements for different microclimate and thermal comfort indicators derived from random forest models. Importance of landscape elements for (a) AT, (b) WS, (c) MRT, (d) PMV.

3.3.2 Nonlinear Effects of Individual Landscape Elements

One-dimensional partial dependence plots (PDPs) further reveal nonlinear response patterns of thermal indicators to individual landscape elements (Figure 6).

For AT, increasing vegetation proportion shows a mild overall cooling trend with limited magnitude. Increasing building proportion reduces AT at low levels but plateaus at medium to high proportions, indicating diminishing marginal shading effects. Pavement and farmland PDPs exhibit complex, non-monotonic patterns, suggesting context-dependent responses. For WS, building proportion shows a near-monotonic negative relationship, with vegetation also reducing wind speed but to a lesser extent, while water bodies and pavement have negligible effects. For PMV, vegetation proportion exerts the strongest influence: increasing vegetation leads to pronounced reductions in both metrics, with accelerated declines at medium to high proportions, confirming the sustained effectiveness of vegetation shading. Pavement significantly elevates PMV, while building effects are more moderate and highly dependent on spatial configuration (LIN & GUI 2024).

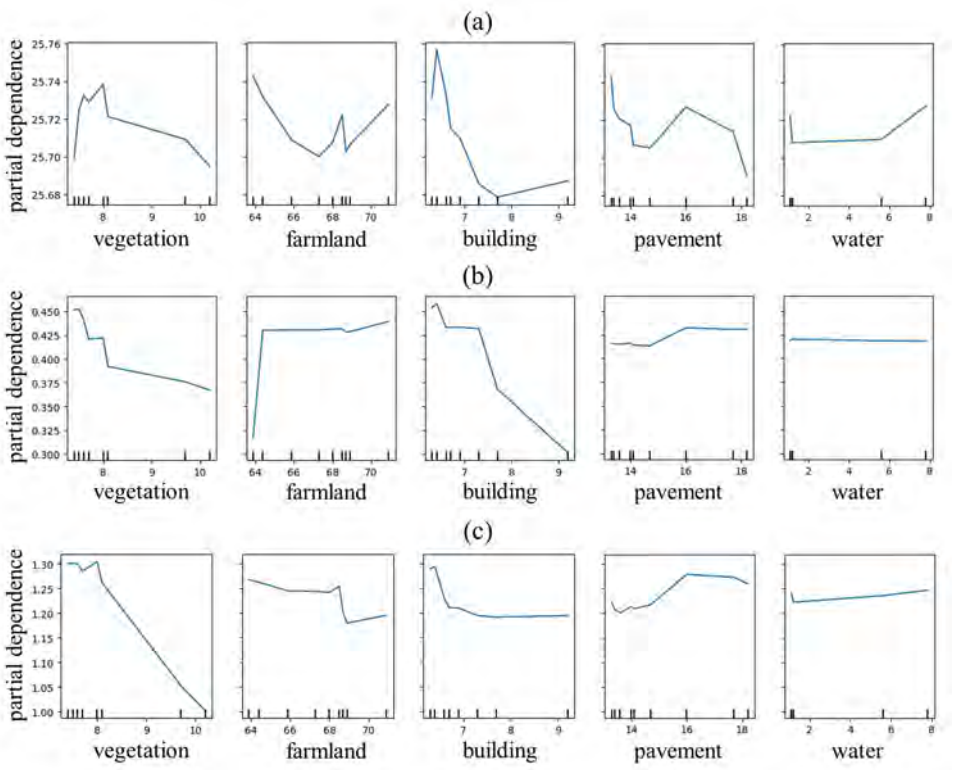

Fig. 6: One-dimensional partial dependence plots for (a) AT, (b) WS, (c) PMV

4 Conclusion

Extreme-heat risk in rural areas is rising, yet planning-oriented evidence remains limited. Using a typical Linpan settlement on the Chengdu Plain, this study combines planning scenarios, ENVI-met simulation, and machine-learning attribution to quantify how five elements – vegetation, water bodies, buildings, paving, and farmland – shape microclimate and thermal comfort and to identify key drivers and interactions for climate-adaptive option selection. Results show strong spatial boundaries at the Linpan-unit scale: courtyard cores remain largely stable across scenarios, indicating the inherent buffering capacity of the Linpan structure. Among elements, tree vegetation most effectively improves comfort (PMV) via shading, while water bodies cool air temperature but with localized comfort benefits that decay with distance. Buildings and paving have limited direct effects on air temperature, but their combined increase can amplify thermal discomfort, especially where shading and ventilation are constrained. Overall, the findings support a planning strategy that prioritizes vegetation as the primary buffer and manages built-paved intensification through spatial organization.

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Cool Forest: Trees as Atmospheric Infrastructure and an Atmospheric Commons

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Abstract: Cool Forest is a living pop-up laboratory that investigates trees as atmospheric infrastructure and as an atmospheric commons capable of mitigating urban heat island effects and improving air quality under climate change. Conceived as both installation and experiment, the project examines how trees function as active agents within urban climates through intertwined biological, chemical, and atmospheric processes. A planting matrix of tree species is augmented by a bespoke, multi-modal sensor network measuring air temperature, humidity, heat index, soil moisture, and sap flux. These measurements are communicated in real time through spatial actuators, living vegetation, and a web-based interface, forming a cybernetic feedback system. Empirical results demonstrate microclimatic cooling and species-specific physiological responses to heat stress, reframing landscape architecture as the design of sensing ecologies and adaptive atmospheric infrastructure.

Keywords: Air quality, urban heat island mitigation, climate adaptation, sensor networks, ecological infrastructure

1 Introduction

The *Cool Forest* project is a living pop-up laboratory designed to demonstrate and visualise the influence of trees on urban air quality and the urban heat island (UHI) effect through the interplay of biological, chemical, and atmospheric processes. Conceived as both installation and experiment, *Cool Forest* investigates how trees function as active agents within urban climates to simultaneously act as filters, producers, and regulators of the city's air. The project situates the tree canopy not as static vegetation but as a porous atmospheric infrastructure, facilitating a continuous exchange between vegetation, air, and the built fabric of the city. Through the deployment of a bespoke sensor network, the project renders visible the thermodynamic and metabolic interactions that constitute the city's atmospheric commons.

The sensor network actively displays the measured data in real-time to communicate how the canopy operates as an intensive modulator of the urban atmosphere. In this manner, trees are evidenced not simply to be static objects in space but as active atmospheric agents. The research argues for a reconceptualization of trees as effective fields, shifting them from the static geometry of building blocks to an extensive geometry displaying intensive gradients of temperature, vapour, and flux materializing the air as a dynamic field of interaction. Furthermore, the selected trees represent species that are expected to be better adapted to future climate conditions in Venice. These species also represent different functional groups and physiological adaptations to extreme heat and drought, thereby allowing observations of climate-stress responses and the potential to maintain the cooling benefits of trees when they are needed most.

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The measured data collected across a range of urban sites demonstrates how trees can be quantified and evidenced as urban sensors and mediators, translating atmospheric flux into form, comfort, and ecological intelligence. Augmented by the sensor network, the trees can be seen to create a living interface between the Biosphere and Technosphere, a kind of 'atmospheric commons' that connects human and nonhuman actors through shared air. This work blurs the boundaries between the Biosphere and Technosphere, augmenting the atmospheric commons that connects human and nonhuman actors through information and perception as well as shared air.

2 Method

The *Cool Forest* installation is designed as a dense planting matrix of local and climate-adapted tree species selected to mimic the natural competition, growth, and resilience of native forests. The species selection anticipates 'future visitor' trees expected to thrive under future climatic conditions, thus functioning as both a biotic forecast and an adaptive experiment.

A distributed sensor network was fabricated and deployed within the installation and across a range of urban test sites. Each sensor node measures key microclimatic variables: air temperature, relative humidity, and the heat index as a perceived temperature relative to human comfort. Additional temperature and humidity sensors distributed throughout the Venetian Lagoon allow direct comparison between the *Cool Forest* microclimate and the wider urban fabric.

Crucially, the system integrates thermal dissipation probes that measure sap flux rates within trees quantifying transpiration as both a biological and atmospheric event. Sap flux velocity (cm/hr) is visualized through LED indicators showing direction and rate, providing real-time feedback on tree stress, cooling activity, and water movement.

Data streams from these sensors are aggregated into a digital repository of heat data, allowing correlation between physiological and atmospheric readings. This live sensing infrastructure positions the pavilion as an instrumented landscape, transforming environmental processes into perceivable phenomena. The project thus functions simultaneously as an environmental monitor, a pedagogical tool, and an atmospheric experiment.

3 Multi-Modal Sensing and Atmospheric Communication

Central to *Cool Forest* is a deliberately multi-modal sensing and communication approach that operates across biological, technological, and perceptual registers. The project integrates conventional environmental sensors measuring air temperature, relative humidity, soil moisture, and sap flux. These measurements are complemented by the Heat Index, which combines air temperature and relative humidity to approximate a human-perceived equivalent temperature, that is, the temperature as it is experienced by the human body.

Bespoke sentinels were designed and fabricated to house the sensors together with actuators that translate these measurements into spatial and visual cues within the installation. While the sensors themselves remain largely invisible, their outputs are continuously communicated

through real-time coloured light strips that modulate in intensity, direction, and hue in response to measured atmospheric conditions. These actuated signals function as an immediate, embodied interface, allowing visitors to register the thermal and physiological states of the forest without recourse to numerical abstraction. In this way, the sentinels render hyper-local atmospheric conditions legible, while simultaneously describing gradients of effect across the installation. Subsequently the glow of the lights creates an ethereal aesthetic that gestures to a space of exchange and affect, a space of shifting intensities and gradients not limited by its physical extensive limits.

In parallel, the trees themselves operate as living sensors, in which variations in leaf turgor, transpiration rates, canopy density, and overall vitality provide a slower, biological inscription of atmospheric conditions. These vegetal responses reveal patterns of heat stress, hydration, and adaptive capacity over time. Operating on a different temporal register than electronic sensing, this mode of biological signalling introduces lag, resilience, and threshold effects that are critical to understanding ecological response under thermal stress.

Complementing these in situ modes, a web-based platform aggregates and visualises all sensor streams in real time, enabling users to compare and contrast microclimatic conditions within the installation against distributed sensors across urban spaces, gardens, and the Venetian lagoon. Together, these layers form a cybernetic communication loop in which data circulates between atmosphere, vegetation, sensors, actuators, and human observers. Measurement is thus transformed into designed feedback, and sensing becomes not merely an analytical tool but an atmospheric language, one that renders invisible processes perceptible, comparable, and actionable within the practice of landscape architecture.

4 Outcomes

4.1 Microclimatic Cooling and Transpiration

Empirical data collected during summer conditions demonstrate that urban trees and forest create measurable cooling effects within the urban microclimate through the combined effects of solar shading and transpiration. Through the phase change of water (liquid to vapour), latent heat is absorbed from the surrounding air, lowering ambient temperatures. The cumulative effect of multiple trees produces zones of evaporative cooling that have the capacity to form gradients of temperature and humidity that extend beyond the canopy perimeter.

Temperature and humidity sensors were located within the Cool Forest and multiple urban forest typologies observed in the city and surrounding region. These include a single planted tree located in a piazza (Chiesa di Sant'Anna), a young planted forest in a garden landscape (Giardino delle Vergini), a mature forested park (Giardini della Biennale), a forested natural area on a nearby island (Le Vignole). Additionally, sensors were located at the Arsenale adjacent to the Cool Forest and the lagoon at a marsh restoration site. Within Cool Forest, 16 sensors were temperature and humidity sensors were installed at two different strata (1.5 m and 2.5m), two paired sensors were installed outside and adjacent to the Cool Forest at 1.5 m, and 5 paired sensors were located in different urban greenspace typologies in greater Venice, including forest park scape, a community garden in a vacant lot, forested natural areas, and the tidal wetland in the Venice Lagoon. Sensors collected data at 30 second intervals from May 1 to November 1.

Sap flux sensors were installed on 12 trees, representing 4 species (n=3). The sensors were installed 20 cm from the root collar on the north face of the tree and measured sap flux (cm/hr) at 15minute intervals from May 1 – November 1. Soil moisture, soil temperature, and air temperature at 10 cm above the soil were installed in all trees monitored for sap flux. These sensors recorded data at 15 second intervals.

We analysed microclimate data collected across Venice and within the Cool Forest by comparing mean temperature, humidity, and heat index for eight 3-hour periods of the day (5:00-8:00, 8:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-20:00, 20:00-23:00, 23:00-2:00, and 2:00-5:00). We use local weather station data (Venice Weather Station at Lido) as a reference to calculate a relative difference in observed temperature and humidity, highlighting the variability between the microclimates one experiences in a city with what is reported. A repeated-measures ANOVA and Tukey's post hoc test were used to analyse differences in cooling effects among urban forest typologies (All analyses were conducted in R version 4.5.2, http://www.r-project.org). We observe significant differences in temperature, with Cool Forest and urban forest sites, generating cooling benefits during the daytime hours (Figures 1-3). When using heat index as a metric of analysis, we found all urban forest landscape typologies provide a cooling benefit across the entire summer, most notably during afternoon hours. These benefits were exacerbated during periods of extreme heat. Within Cool Forest we observed significantly different microclimates between planter bed and location, a product of time of day (solar access) and edge and interior dynamics of the designed forest (Figure 4).

Measured sap flux detected species-specific differences in transpiration rates and responses to periods of intense heat (Figure 5). Such variation is representative of the different functional traits and adaptation response of the selected species to heat and drought stress. For example, some species, such as *Acer Monspessulanum* close their stomata during intense heat, thereby reducing heat stress, but also transpirative cooling. Other species, such as Pistaccia Terebinthus, keep their stomata open, and risk heat-related stress while maintaining higher rates of transpiration, and the associated cooling benefits Ecologists and designers are now working with these functional groups to identify species that will persist in urban environments and climate futures, while providing maximum cooling benefits when needed most. Sap flux reveals a critical physiological, and hidden, process that contributes to urban heat island mitigation and human comfort, as well as an early indicator of stress and/or adaptive capacity of these tree species to the present and future climate of Venice. In doing so, the visitor engages with data to understand how trees modify our environment today and the vulnerability of these organisms to shifting urban- and regional-climate conditions.

4.2 Sensor Data and Visualization

The real-time sensor interface communicated these complex processes as dynamic visual phenomena transforming invisible atmospheric exchanges into visible, legible form. Visitors could perceive the 'breathing' of the canopy through fluctuating temperature, humidity, and sap flux data displayed across the forest. This performative feedback revealed trees as both active agents and living sensors, translating atmospheric flux into ecological intelligence.

As the destructive debate about climate change (unfortunately) continues, the sensor network serves as an evidentiary mechanism, demonstrating the real and positive effects that incorpo-

rating trees can have in our cities to naturally mitigate rising urban temperatures, air pollution, and increasing energy use (and cost) as mechanical air conditioning use rises. This technology provides Landscape Architects with a deployable tool to demonstrate ecosystem services as a measurable, quantifiable and performative activity. It also helps to perceptively shift the integration of vegetation to be a vital urban infrastructure, acting as an 'atmospheric commons' that supports the collective health and well-being of the city, its human occupants, and its non-human residents.

5 Discussion

Urban Heat Island and Thermal Commons

The UHI effect arises when common urban materials absorb and retain solar radiation, releasing it slowly as heat. The loss of vegetative cover, the emission of waste heat from vehicles and industry, and restricted air movement due to urban geometry amplify this effect, producing temperature differentials of 1-7°C higher relative to rural surroundings. *Cool Forest* demonstrates that shading, evapotranspiration, and air circulation by trees collectively reverse these conditions by converting sensible heat into latent heat and facilitating convective air exchange.

When replicated at urban scales through green corridors, parks, and vegetated façades, such systems can transform the city from a heat-storing mechanism into a porous, breathing organism. The resultant cooling plumes coalesce to form what we term a 'thermal commons' a shared atmospheric space moderated by vegetation rather than mechanical systems.

Trees as Atmospheric Infrastructure

From a landscape architectural perspective, trees can be reconceptualised as atmospheric infrastructures – living thermodynamic agents that modulate temperature, humidity, and air chemistry. Their continuous exchange of gases, heat, and moisture materialises the air as a dynamic, relational field rather than a static void. In this view, trees operate as urban sensors and mediators, linking the biosphere and Technosphere through shared atmospheric processes. This perspective shifts focus from object-based design to field-based design, where gradients of temperature, vapor, and flux constitute the true geometry of urban form.

Design and Theoretical Implications

The findings advocate for the integration of sensing technologies within landscape architecture to render ecological processes visible, quantifiable, and necessary. The project aligns with Deleuze and Guattari's conception of intensive systems, where transformation occurs through gradients and continuous modulation rather than discrete elements. In Cool Forest, the tree canopy becomes a porous atmospheric interface. In this sense, it not only measures the urban atmosphere but performs it as an aesthetic, scientific, and ecological practice that collapses the boundary between data, experience, perception, and living systems.

6 Conclusion

Cool Forest redefines infrastructure as a living cybernetic field, an emergent network of vegetal, atmospheric, and technological components engaged in continuous feedback. In this work, trees and sensors form an adaptive infrastructure of sensing and exchange, where biological and digital processes are intertwined. The project demonstrates that environmental infrastructure can be self-modulating, learning, and performative, an ecology that measures itself and responds to its own signals and transforms accordingly.

Within this framework, the distinction between living and non-living, natural and artificial, human and nonhuman become porous. The sap flux within a tree and the electrical current within a sensor are not opposites but parallel forms of information transfer, distinct circuits within a shared thermodynamic continuum. Heat, vapour, voltage, and data constitute a single informational metabolism, a cybernetic assemblage through which matter and meaning co-evolve. *Cool Forest* thus materialises a planetary medium where organic and inorganic agents participate in the same communicative and energetic exchanges.

As an infrastructural design practice, *Cool Forest* suggests that future cities can operate as sensing ecologies, distributed, self-aware systems that can be designed to register and regulate their own atmospheres. The project's sensor-augmented trees demonstrate how environmental feedback can be designed as a material condition embedded within living systems to generate adaptive, collective intelligence. This is not infrastructure imposed upon nature but infrastructure as nature, an entangled field of flux that cools, cleans, and computes simultaneously.

Cool Forest advances a cybernetic design paradigm for landscape architecture. Here, *infrastructure becomes atmospheric, landscape becomes computational, and the atmosphere becomes the interface*. The project reframes design as an act of modulating feedback, situating trees and sensors as co-extensive agents within a planetary network of sensing and exchange. In doing so, it cultivates an approach to designing atmospheric infrastructures, cooling forests, vegetated corridors, and sensor-augmented landscapes that regenerate the urban atmosphere as a shared, living commons.

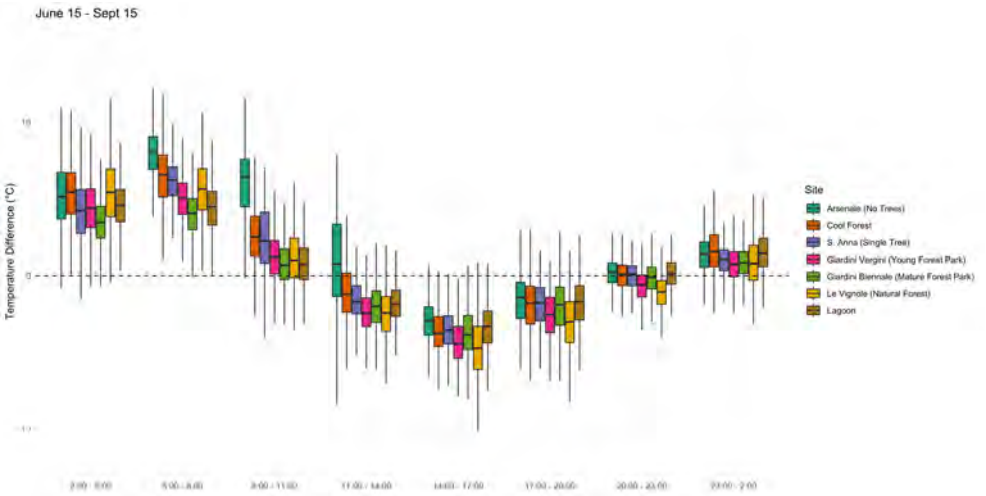

Fig. 1: Mean temperature difference (degrees Celsius) from urban forest typologies as related to the Venice weather station at Lido. Temperatures are reported as the mean for eight 3-hour periods of time (5:00-8:00, 8:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-20:00, 20:00-23:00, 23:00-2:00, and 2:00-5:00) for all data collected from June 15 to September 15.

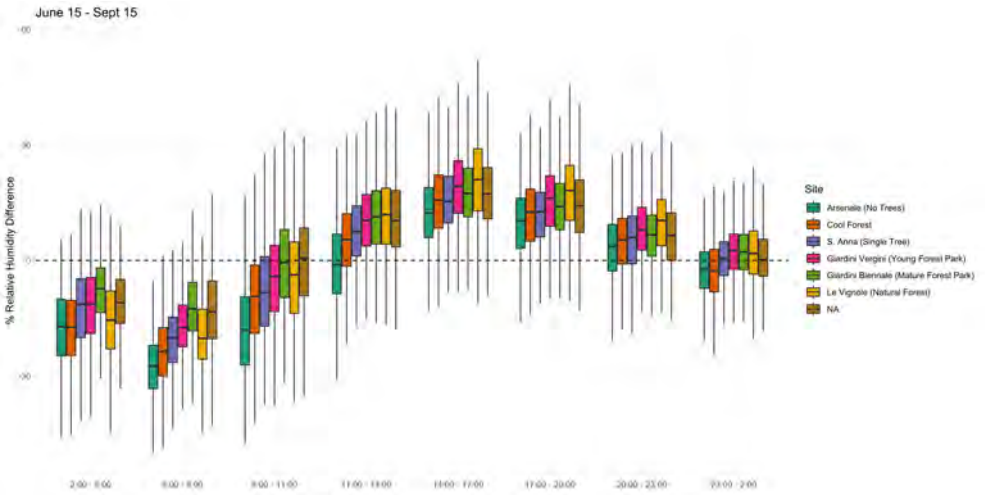

Fig. 2: Mean relative humidity difference (% relative humidity) from urban forest typologies as related to the Venice weather station at Lido. Relative humidity are reported as the mean for eight 3-hour periods of time (5:00-8:00, 8:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-20:00, 20:00-23:00, 23:00-2:00, and 2:00-5:00) for all data collected from June 15 to September 15.

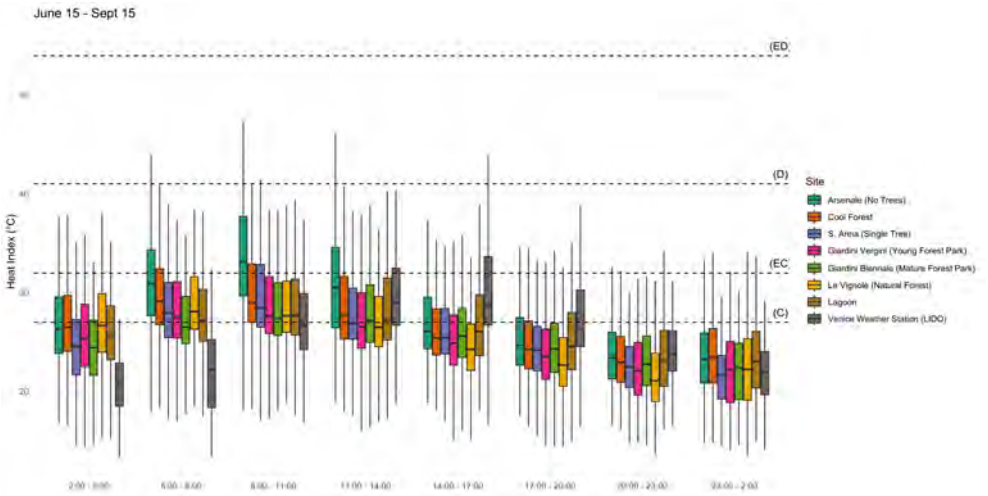

Fig. 3: Mean heat index for urban forest typologies and the reference site (Venice weather station at Lido). The index, which is calculated from temperature and relative humidity values, is reported as the mean for eight 3-hour periods of time (5:00-8:00, 8:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-20:00, 20:00-23:00, 23:00-2:00, and 2:00-5:00) for all data collected from June 15 to September 15. Following the weather US National Weather Services heat index, advisory levels are denoted as: "C", Caution, fatigue possible (27-32 C), "EC", Extreme Caution, exhaustion likely (32-41 C), "D", Danger, heat stroke probable (41-54 C), and "ED", Extreme Danger, heat stroke imminent (>54 C).

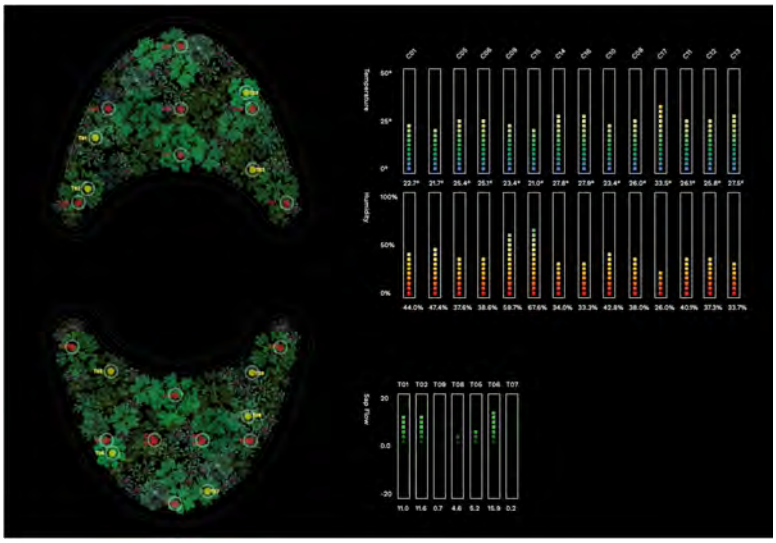

Fig. 4: Microclimate within the Cool Forest. Sensors are installed in an array across the Cool Forest and to monitor and display temperature (top right), humidity (middle), and heat index in real time.

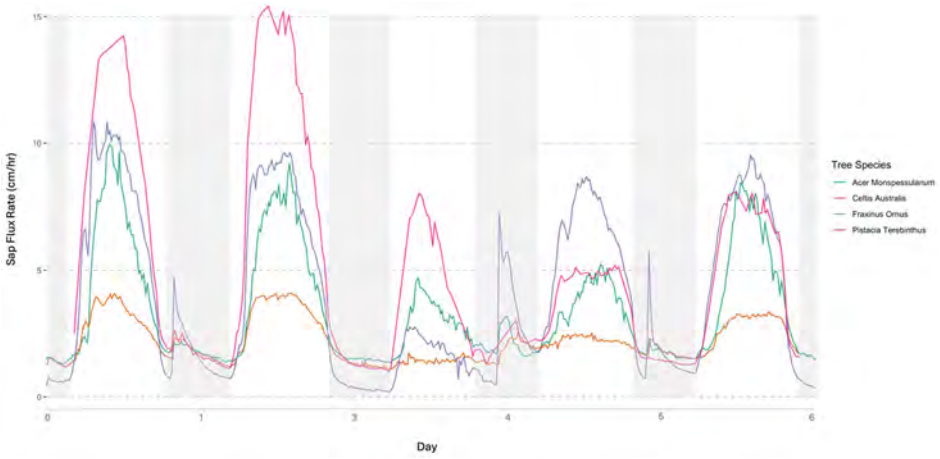

Fig. 5: Sap flux rate for four tree species in Cool Forest (June 6-10). Sap flux follows diurnal patterns of maximum flow during peak daylight and temperature hours. Maximum sap flux rates, and thus transpiration associated cooling benefits, differ between species. Species exhibit different responses to heat stress. For example, June 8 ("Day 3") was abnormally hot and humid, the stress response caused trees to reduce sap flux rates. Nocturnal recovery of stem water, night sap flux, is observed, especially in Fraxinus Ornus.

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Research on the Algorithm and Its Simulation Application of Damaged Space in Urban Coastal Landscape Based on Clustering Recognition Model

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Abstract: In the context of marine sustainable development and resilient city construction, systematically conducting precise identification and evolution analysis of damaged space in urban coastal landscape has become an important topic in current coastal landscape protection and restoration practices. Based on Nature-based Solutions, this study constructs an analytical framework for clustering recognition and simulation application of damaged space in coastal landscapes, interpreting and analyzing the evolutionary trends and driving mechanisms of coastal landscape damage. An empirical study is conducted in the typical coastal zone of Yancheng City. Using landscape type and driving factor data from 2010 to 2020, a clustering recognition model is established by integrating the PLUS model with spatial autocorrelation analysis methods to simulate the evolutionary trends of damaged space in the coastal landscape. The Geographic Detector is further employed to reveal the impacts of driving factors and their interactions on the differentiation of damaged space. The results indicate that from 2010 to 2030, the damaged space of the coastal landscape exhibit a gradient evolution characteristic, shifting from coastal agglomeration to inland expansion (Moran's I > 0.6). The clustering model identifies five types of damaged space, with high damage regions concentrated in coastal wet-lands, reclamation areas, and urban expansion belts. Vegetation scale, climatic temperature, regional economy, and land-use type adjustments are key variables influencing the evolution of landscape damage (q > 0.15). Corresponding restoration and renewal efforts need to be coordinated based on the mechanisms combining different levels of landscape damage zoning and key driving factors. The findings validate the effectiveness of this analytical framework in the dynamic characterization and mechanism analysis of coastal damaged space, providing methodological support and technical pathways for the zonal restoration and resilient management of coastal urban landscapes.

Keywords: Coastal landscape, damaged space, space algorithm, clustering recognition model, evolution simulation

1 Introduction

Building resilient, healthy, and beautiful coastal landscapes is an important lever for promoting land-sea coordinated development and ensuring the ecological security of coastal cities (PETRIȘOR et al. 2020). As the ecological barrier and resource carrier for coastal cities, coastal landscapes possess multiple functions such as ecological regulation, environmental stabilization, and risk buffering. With the continuous superimposition of climate change and human activities, coastal landscapes currently commonly exhibit a damaged state characterized by structural degradation and functional decline (GUO 2022). Under the guiding concept of nature-based solutions, current coastal landscape research is gradually shifting from ecological function assessment to the analysis of disturbance mechanisms and the construction of resilience processes (LI et al. 2017, ZHANG 2023), placing higher demands on understanding the response mechanisms and regulatory mechanisms of coastal landscape systems. Scientifically identifying and analyzing damaged spaces in coastal landscapes, and revealing and an-

Journal of Digital Landscape Architecture, 11-2026, pp. 549-562. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-770-0, ISSN 2367-4253, doi:10.14627/537770053.

alyzing their damage characteristics and evolution mechanisms, hold significant research value and practical importance for cultivating urban coastal landscapes that are warm, controllable, and restorable.

Landscape damaged spaces are spatial units where the ecological structure and function continuously degrade due to natural changes or human disturbances, reflecting the response and recovery capacity of landscape units under external pressures and internal vulnerability. Their evolution process directly affects the stability and sustainability of the landscape system (CUI et al. 2021, CUI et al. 2025). Research on landscape damage was initially applied in fields such as urban landscape pattern analysis (CHEN et al. 2024), ecosystem function assessment (GUO 2022), and land use change monitoring (TANG et al. 2020). In recent years, the research focus has shifted to the temporal evolution, type differentiation, and process mechanisms of degraded spatial units, promoting the expansion of research on landscape damaged spaces from pattern analysis to process construction (ZHANG et al. 2025). However, existing research on damaged spaces in coastal landscapes mostly focuses on areas such as land use conflicts and ecosystem service degradation (ZHANG et al. 2024), emphasizing static assessment, and still lacks systematic exploration of the identification and dynamic characterization of damaged spaces. It is noteworthy that even in coastal landscapes dominated by natural elements, functional coupling imbalances and structural continuity interruptions may conceal damaged states (LIN & YU 2018). Therefore, scientifically constructing a characterization system and evolution analysis pathway for damaged spaces in urban coastal landscapes is crucial.

Nature-based Solutions typically leverage the resilience and spatial heterogeneity of the system itself, identifying key ecological nodes and corridors for hierarchical zoning to provide differentiated strategies for landscape conservation and restoration (PITTMAN et al. 2022). As a digital tool for objectively mining spatial patterns and evolutionary models, the clustering recognition model can, by characterizing the internal hierarchical structure, agglomeration characteristics, and differentiation patterns of damaged space, provide spatial units and quantitative basis for the precise identification and zonal restoration of damaged space. Currently, traditional assessments of coastal landscape changes mostly rely on multi-temporal remote sensing data for analysis, and have made initial progress in analyzing landscape change hotspots and identifying the temporal characteristics of degradation processes (CHEN et al. 2022). However, on the one hand, relevant studies often remain at the stage of describing change phenomena; on the other hand, there are still many scale dependencies in the evolution analysis of damaged space in coastal landscapes, and the accuracy of evolution simulation and the explanatory power of mechanisms still need improvement.

As an effective tool for simulating landscape evolution, the PLUS model can dynamically deduce landscape type transitions and quantitatively analyze the contribution of driving factors under the support of multi-source data, through mechanisms such as random seed generation and multi-factor driving（XU et al. 2025). Traditional methods, such as CAMarkov and FLUS models, have limitations including insufficient characterization of complex nonlinear interactions and sudden disturbances, and relatively weak depiction of multi-driving force coupling mechanisms (GHOSH et al. 2017). In contrast, the PLUS model, based on the Land Expansion Analysis Strategy (LEAS) and the Cellular Automata for the fine-scale generation of land-use patterns (CARS), can more finely depict the nonlinear changes and threshold mutation characteristics of coastal landscapes during disturbance and recovery processes (LIANG et al. 2021). It also integrates multiple patch evolution rules and scenario constraints,

enhancing spatiotemporal consistency and explanatory power in simulating damaged space evolution.

Against this backdrop, we propose an innovative method to reveal the formation mechanism and evolution patterns of landscape damage through clustering recognition and dynamic simulation technologies. Taking the typical coastal zone of Yancheng City as the study area, we integrate multi-source data to build a driving factor database, combine mathematical statistics to establish a clustering recognition model for damaged space, conduct identification of damage type differentiation and detection of temporal changes in damaged space, establish an evolution simulation system for damage types based on the PLUS model, validate the action modes and interaction mechanisms of main driving factors, and discuss zoning restoration strategies based on response processes. This study provides technical support and methodological insights for the conservation, restoration, and restoration practices of urban coastal landscapes.

2 Methodology

2.1 Technical Process

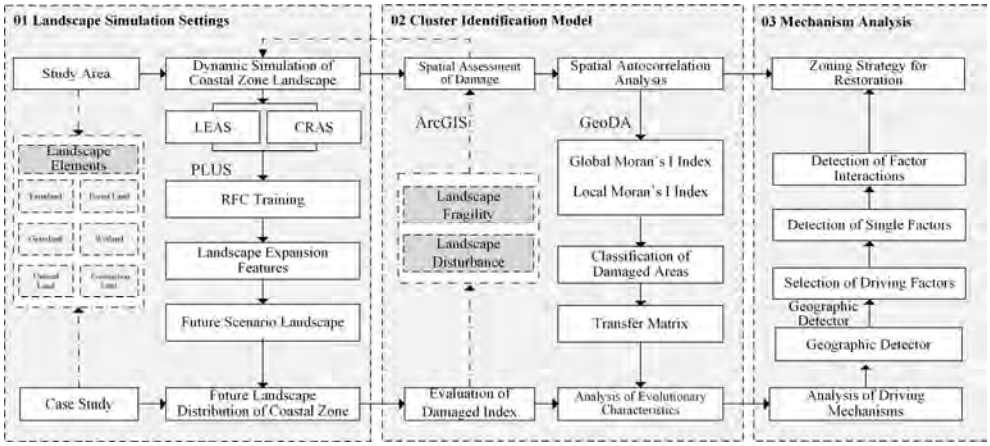

Fig. 1: Technical process

This study takes multi-temporal landscape type data and multi-source driving data as the research objects, proposing a method for coastal landscape damaged space algorithm and evolution simulation based on a clustering recognition model. This method integrates landscape simulation models with spatial autocorrelation analysis techniques to establish a clustering recognition model for coastal landscape damaged space, and combines algorithms such as Kriging interpolation and the Geographic Detector to form an analytical process of "dynamic simulation – type identification – mechanism analysis" (Figure 1). Compared with traditional GIS-based landscape change assessments, this research process is oriented towards the intervenability of damaged space. Based on the deduction of temporal evolution and the identification of type differentiation, it translates changes in damaged space into dam-

age types oriented towards zonal restoration and their dominant driving mechanisms, providing a quantitative basis for decision support in coastal landscape planning and restoration.

2.2 Space Algorithm

To quantitatively characterize the degree of coastal landscape damage, this study constructs a comprehensive index system to characterize the resilience response state of landscape units under external disturbances (DE MONTIS et al. 2020). The index consists of two types of indicators: landscape disturbance degree and vulnerability. A spatial grid division is used to generate basic analysis units. After normalization, the damage value for each landscape type is calculated, thereby obtaining the landscape damage index at the grid scale. Spatial autocorrelation analysis methods are then employed to establish a clustering recognition model for coastal landscape damaged space (Equations (1-2)).

$$R_i = \sqrt{S_i \cdot F_i} \tag{1}$$

$$\mathrm{ERI}_k = \sum_{i=1}^{N} \frac{A_{ki}}{A_k} R_i \tag{2}$$

Where S_i is the landscape structure index; F_i is the landscape vulnerability index; ERI_k is the landscape damage index of the *k*-th grid; A_{ki} is the area of landscape type *i* within the *k*-th grid; A_k is the area of the *k*-th grid; R_i is the landscape loss degree index of landscape type *i*; *N* is the number of landscape types within the grid; *i* represents six landscape types: farmland, woodland, grassland, wetland, unused land, and construction land.

Landscape damaged space may exhibit specific agglomeration characteristics within geographic neighborhoods (ŞENAY & NURLU 2024). To identify the correlation of damaged space in the coastal landscape, this study introduces global Moran's I and local Moran's I for spatial autocorrelation analysis (Formula 3). The significantly clustered units are screened through significance testing ($p < 0.05$) to determine the clustering results of damaged space, providing a data foundation for subsequent zonal restoration of coastal landscapes.

$$I = \frac{n}{\sum_i \sum_j w_{ij}} \cdot \frac{\sum_i \sum_j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \tag{3}$$

Where *I* is Moran's I; n is the number of spatial units; x_i and x_j are the observed values of units i and j. A significantly positive *I* indicates a spatial positive correlation among areas with high or low damage values.

Nature-based Solutions emphasize implementing precise management based on the spatial heterogeneity of ecosystems. Systematically analyzing the evolution driving mechanisms of coastal landscape damaged areas has become key to implementing differentiated restoration and regulation strategies for coastal landscapes (XU & MATSUSHIMA 2024). To analyze the driving mechanisms of damaged space, this study employs the Geographic Detector model to assess the explanatory power of driving factors on the differentiation of damaged space. Single-factor detection calculates the q-value for each factor to screen the main influencing factors. Furthermore, interaction detection analyzes the synergistic and nonlinear effects between factors, quantifying the contribution of factor combinations to the differentiation of damaged space (Formula 4).

$$q = 1 - \frac{ssw}{ssT} \times \frac{N-L}{N-1} \tag{4}$$

Where ssw is the total within-stratum variance; ssT is the total variance of the entire region; N is the total number of samples; L is the number of strata. q ranges within (0, 1], with larger values indicating stronger explanatory power of the factor for the differentiation of damaged space.

2.3 Evolution Simulation

As a key technology for analyzing the dynamic evolution process of landscapes, landscape simulation can effectively predict the evolution trends of urban coastal landscape patterns and has become an important basis for assessing coastal regional development and spatial planning (SHE et al. 2017). To predict trends in coastal landscape change, this study employs the PLUS model to construct a landscape simulation framework (Fig 2). The model utilizes the LEAS module to mine the expansion patterns of landscape types during the historical period and calculates the expansion probability of each landscape type based on driving factors. On this basis, the CARS module integrates the aforementioned expansion probabilities with conversion rules, simulating the complex nonlinear change process of landscape types in spatial and temporal dimensions by randomly generating multi-type landscape patches. This ultimately produces predictive results for coastal landscape simulation (Equations (5-6)).

$$P_{i,k(X)}^{d}=\left(\sum_{n=1}^{M} I\left[\mathrm{h}_{n}(X)=d\right]\right) / M \tag{5}$$

Where $P_{i,k(X)}^{d}$ represents the probability of land parcel i converting to landscape type k, where d takes a value of 0 or 1; d=0 indicates that conversion to landscape type k is not possible, and d=1 indicates that conversion is possible. X represents the driving factors; I represents the decision tree index function; M represents the total number of decision trees.

$$OP_{i,k}^{d=1,t}=P_{i,k(X)}^{d} \times \Omega_{i,k}^{t} \times D_{k}^{t} \tag{6}$$

Where OP represents the overall conversion probability; Ω represents the neighborhood effect of the land parcel unit; D represents the influence of the future demand for landscape type k.

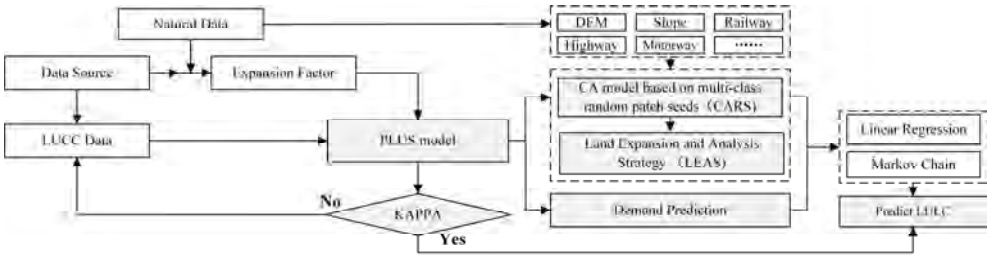

Fig. 2: Diagram of coastal landscape damaged area evolution simulation

The study selects the coastal zone in Yancheng City, Jiangsu Province as the research area, with a total area of 10,480 km², covering coastal counties and cities such as Binhai, Xiangshui, Sheyang, Tinghu, Dafeng, and Dongtai (Figure 3). A 2.5km × 2.5km grid division was used to generate 2168 spatial units. The model was constructed based on landscape type data from three periods (2010, 2015, and 2020). Parameter training was conducted using 2010–2015 data, with parameters calibrated through cross-validation. Subsequently, accuracy was verified using 2020 data, and based on this, the spatial distribution of landscape damage in 2030 was simulated. Building on this, global and local Moran's I were employed to identify the agglomeration characteristics and distribution patterns of the damaged space. By comparing the explanatory effects of different discretization methods, the optimal discretization scheme was determined based on the maximum q-value in the highest quantile interval. Based on this, factor detection and interaction analysis were conducted to systematically reveal the key driving mechanisms behind the evolution of coastal landscape damaged space.

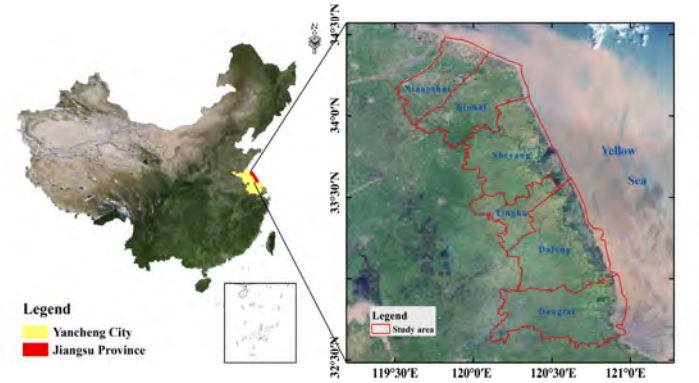

Fig. 3: Schematic diagram of the Yancheng coastal area

Table 1: Dataset of driving factors for the coastal landscape in Yancheng City

Driving Factors	Data	Data Sources
Natural Aspects	Digital Elevation Model (DEM)	USGS/SRTMGL1_003 data
	Slope	USGS/SRTMGL1_003 data
	Aspect	USGS/SRTMGL1_003 data
	NDVI, EVI-based FVC index	MODIS/061/MOD13A1
Climatic Aspects	Annual Mean Land Surface Temperature (LSTd)	MODIS/061/MOD11A2
	Precipitation (Pre)	National Earth System Science Data Center
	Evapotranspiration (ET)	MODIS/061/MOD16A2GF
Human Activity Aspects	Land Use and Land Cover Change (LUCC) Gross Domestic Product (GDP) Population Density (POP)	1990-2020 Land Use Dataset from the team of Huang Xin, Wuhan University
		China's Population Spatial Distribution Kilometer Grid Dataset by Xu Xinliang
		WorldPop Database

3 Discussion of the Results

3.1 Evolution Simulation and Characteristic Interpretation of Coastal Landscape Damaged Areas

Spatial evolution simulation of the coastal landscape was conducted based on multitemporal landscape type data. The results show that the simulation accuracy for the 2020 landscape pattern, driven by data from 2010 and 2015, achieved Kappa > 0.86, indicating strong adaptability of the PLUS model for simulating temporal evolution in coastal landscapes. Building on this, the spatial distribution of the landscape in 2030 was further simulated and predicted (Figure 4). A semi-variance function was used to fit the landscape type data for each period (Nugget/Sill ratio > 0.5). Among these, the Nugget/Sill ratio in 2015 decreased to its lowest during the study period, while the spatial autocorrelation range (Range) reached its maximum (Table 2).

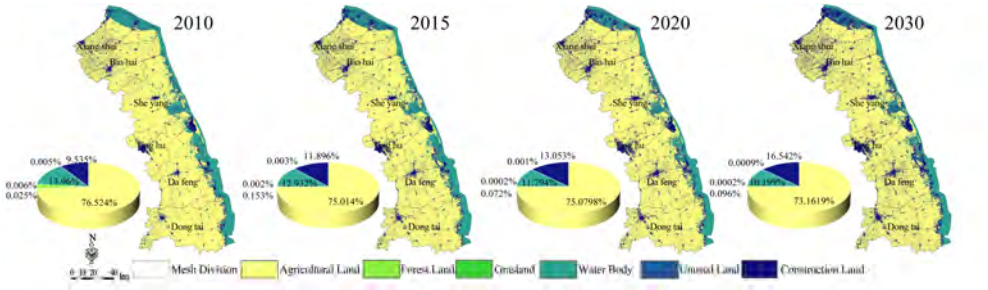

Fig. 4: Spatial distribution map of the coastal landscape in Yancheng City

Table 2: Semi-variogram Values

Year	Model	Nugget	Sill	Range/m	Nugget/Sill
2010	Spherical	0.000113	0.000332	57900	0.661
2015	Exponential	0.000087	0.000187	69000	0.535
2020	Spherical	0.000130	0.000386	57200	0.663
2030	Spherical	0.000749	0.002238	64800	0.665

The clustering model identified five types of damaged areas. The overall study area exhibits a gradient spatial distribution pattern, shifting from nearshore agglomeration to inland expansion (Figure 5). Analysis of the agglomeration characteristics of the damaged areas shows that the global Moran's I values for each period are all positive (Moran's I > 0.6) (Table 3), indicating a significantly positive spatial autocorrelation characteristic for landscape damaged areas within geographical neighborhoods in the study area. In terms of spatial distribution characteristics, high-damage areas are concentrated in Xiangshui County, the northern coastal zone of Binhai County, and the eastern nearshore area of Sheyang County, showing significant agglomeration features. Lower-damage areas are mostly distributed in inland regions such as Tinghu District and Dongtai City, with relatively scattered agglomeration characteristics.

In terms of spatial evolution trends, the medium-damage areas showed the most significant changes during the study period, with their area proportion cumulatively increasing by 9.639%. The period from 2010 to 2015 was a key stage for changes in damaged areas within the study region. After 2015, medium-level damaged areas rapidly expanded to the central part of Sheyang County, the inland area of Tinghu District, and the coastal-inland transition zones of Dongtai City, with their proportion rising to 26.726% by 2030. This process further validates the effectiveness of the semi-variance fitting results. Notably, there is a synergistic growth relationship between damage level and spatial agglomeration characteristics. Farmland landscapes distributed in inland areas serve as transition zones for the rapid expansion of high-damage areas, while the structural characteristics of highdamage areas in nearshore reclamation zones and development fringes remain stable.

Table 3: Moran's I for the Coastal Landscape in Yancheng City

Year	Moran's I	Sd(I)	z
2010	0.6354	0.0103	61.4265
2015	0.5067	0.0096	52.86324
2020	0.6411	0.0104	61.5706
2030	0.6190	0.0076	81.5073

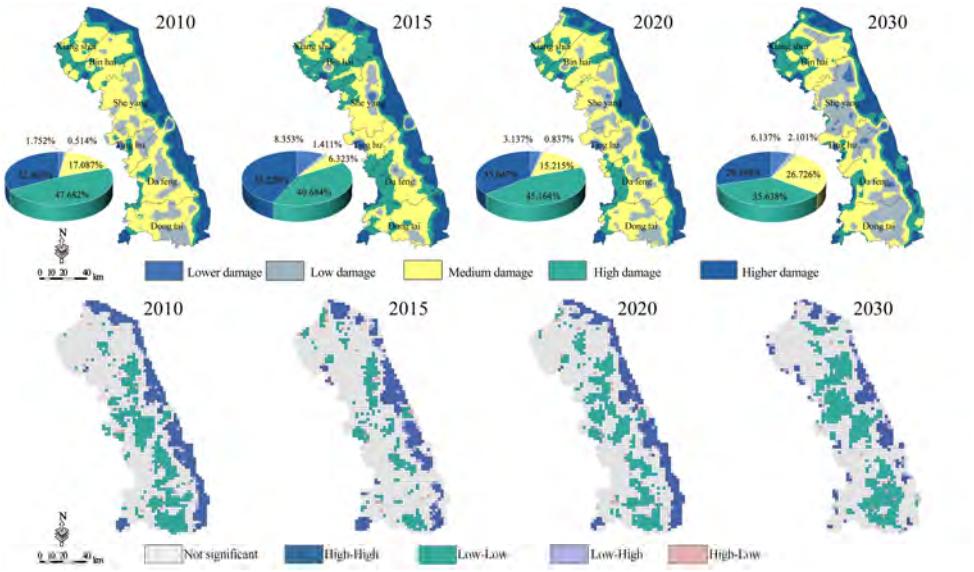

Fig. 5: Spatial distribution and clustering identification of damaged areas in the coastal landscape of Yancheng City

3.2 Driving Factor Interaction Effects on Coastal Landscape Damaged Areas

Based on factor detection and analysis using the Geographic Detector (Table 4), the landscape damage process is influenced by both the natural environment and human activities.

The factor detection results show that vegetation coverage, land surface temperature, and regional economic activity level are the dominant factors affecting the evolution of landscape damaged areas in the study region. Among these, the explanatory power of vegetation coverage and land surface temperature was prominent in 2010 ($p < 0.001$), indicating that the pattern of damaged areas was primarily controlled by natural ecological conditions. By 2015, the explanatory power of precipitation conditions, population density, and evapotranspiration significantly increased ($p < 0.05$), especially in urban expansion frontiers and agricultural land conversion areas, where the expansion rate of damaged areas accelerated. This indicates the deepening influence of climatic fluctuations and human activities on the differentiation of damaged areas. The data show that although vegetation coverage has buffering and regulatory functions within the overall coastal landscape pattern, its regulatory effect on coastal landscape damaged areas is relatively limited under the combined pressure of economic development and thermal effects (THRUSH et al. 2021).

Analysis of the factor interaction detection results (Figure 6) shows that the interaction effects of GDP×LSTd, GDP×Pre, and GDP×FVC are significant ($q>0.15$). This indicates that the combined effects of factors such as economic development and thermal disturbance, precipitation change and vegetation coverage play a dominant role in the formation of landscape damaged areas. In 2015, the interaction between precipitation and population density weakened, while the inter-action between land use change and economic development gradually strengthened. This indicates intensified land-use conflicts during this period, increasing pressure on farmland and wetland landscapes. By 2020, the interaction between land surface temperature, vegetation coverage, and economic activity peaked, reflecting that the synergistic effect of economic expansion and temperature change accelerated the expansion of damaged areas. In summary, the generation and expansion of spatial disturbances often stem from the combined action of multiple dominant factors. In the practice of landscape spatial management and control in coastal zones, focusing on factor combinations with coupling enhancement effects may improve the stability and resilience of the coastal landscape system.

Table 4: Factor detection results for damaged areas in the coastal landscape of Yancheng City

Year	Slope	Aspect	NDVI	FVC	LSTd	Pre	ET	Pop	GDP	CLCD
2010	0.004^{***}	0.006^{*}	0.082^{*}	0.262^{***}	0.244^{***}	0.020^{*}	0.029^{*}	0.041^{***}	0.131^{***}	0.099^{*}
2015	0.004^{***}	0.008^{*}	0.004^{*}	0.104^{*}	0.255^{*}	0.041^{*}	0.056^{*}	0.104^{*}	0.163^{**}	0.053^{*}
2020	0.004^{***}	0.007^{*}	0.015^{*}	0.109^{*}	0.227^{***}	0.111^{***}	0.021^{*}	0.067^{*}	0.164^{***}	0.055^{*}

Note: "***" indicates $p<0.001$, "**" indicates $p<0.05$, "*" indicates $p>0.05$.

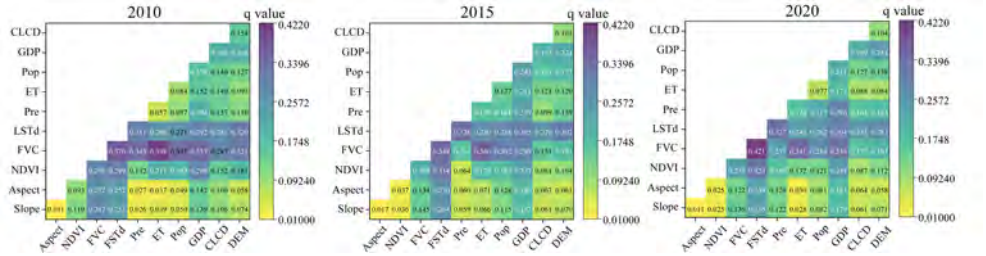

Fig. 6: Factor interaction detection for damaged areas in the coastal landscape of Yancheng City

3.3 Historical Trajectory and Optimization Orientation of Coastal Landscape Damaged Areas

Combining the historical evolution characteristics of different landscape types within the damaged areas (Figure 7), developed construction land shows relatively stable fluctuations in spatial structure, while forested and green space areas, although having the smallest proportion, varied considerably. From 2015 to 2020, the proportion of high-damage areas in woodland increased by 231.7%, and in grassland by 94.5%, indicating a significant intensification of human activity development and vegetation destruction during this stage. Farmland and wet-land, however, showed progressive damage. From 2010 to 2020, the proportion of high-damage areas in farmland increased by 1.9 times, with an increase of 63.9% from 2015 to 2020. Wetlands entered an accelerated damage period from 2020 to 2030, with the proportion of high-damage areas increasing by 29.8%. This indicates that the intensification of intertidal zone development and reclamation activities caused more severe impacts on wetland ecosystems. This finding aligns with research by Zhou Rujia et al., suggesting that among different landscape types, urban expansion and natural landscape degradation are the main driving factors leading to land-scape damage (ZHOU et al. 2016).

Based on this, guided by the concept of Nature-based Solutions, changes in damaged space are categorized into three types for each decade-long period: intensification areas, improvement areas, and stable areas (Figure 8). A comparative analysis of typical cases was conducted to examine the intervention pathways and outcomes for different damage types, thereby enhancing the operability of optimization strategies. During 2010-2020, the coastal fringe of Dongtai District exhibited strip-shaped damage intensification, where the combined effects of port construction and reclamation activities led to particularly prominent fragmentation of wetland landscape patches. Taking the “Returning Aquaculture Ponds to Wetlands” project implemented within this area in the Yancheng Wetland Rare Bird National Nature Reserve as an example, its core intervention measures included removing reclamation pond embankments, reorganizing hydrological units, and restoring tidal exchange through water flow control facilities, thereby reconstructing wetland connectivity at the structural level (WANG et al. 2018). Following project implementation, the wetland degradation rate decreased from 2.48% to 1.24%, significantly improving habitat integrity. This practice demonstrates that for damage intensification areas, hydrological process reconstruction should be prioritized as a precursor, with landscape ecological transition zones laid out accordingly.

Through the engineering combination of “embankment removal – water connection– landform shaping”, the functional transformation of degraded spaces into stable ecological zones can be achieved (ZHANG G. et al. 2025).

During 2020-2030, the damage improvement areas showed a clear trend of expansion in the coastal areas of Sheyang and at the confluence of river networks. This change corresponds to the implementation scope of the Sheyang Coastal Wetland Ecological Restoration Project in recent years (YANG, J et al. 2021). In this region, by optimizing the zoning control structure of coastal wetlands, restricting high-intensity reclamation activities, and implementing halophytic vegetation restoration and the construction of habitat buffer zones, the intensity of human disturbance has been gradually reduced, and the ecological connectivity among wetland patches has been enhanced. Relevant monitoring indicates a gradual improvement in the structural stability and habitat suitability of the wetlands. This pathway provides a practical reference for designers of Nature-based Solutions to replace some hard engineering protection with ecological structures. Therefore, looking towards 2030, it is recommended that on the basis of consolidating hydrological regulation and habitat zoning, vegetation restoration projects should continue to be promoted. For stable damaged space, such as the central coastal zone, a dynamic landscape monitoring and management system emphasizing “low intervention, strong monitoring” should be implemented to achieve long-term resilient development of the coastal landscape (CUI et al. 2025).

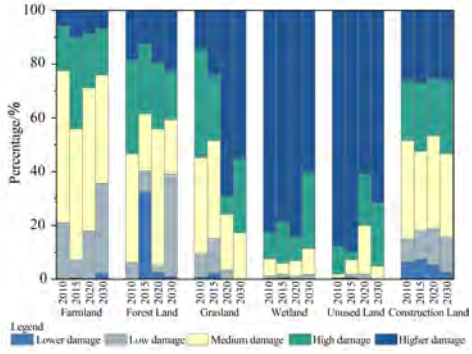

Fig. 7: Changes in damage for coastal landscape types

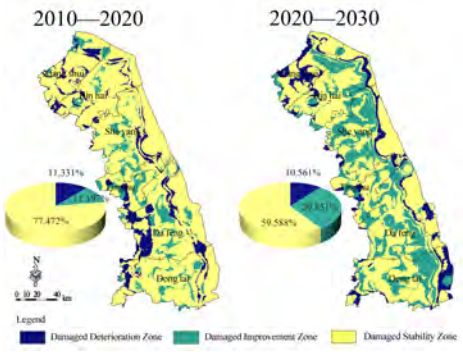

Fig. 8: Restoration zones for coastal landscape damaged areas

4 Conclusion and Outlook

This study focuses on the evolutionary characteristics of damaged space in urban coastal landscapes. By integrating clustering recognition models, landscape simulation, and driving factor detection methods, it constructs an algorithmic workflow for the identification and analysis of damaged space in coastal landscapes. Compared with traditional GIS-based landscape change assessments, which often rely on area statistics and single-period analysis, this study extracts the agglomeration characteristics of damaged space through a clustering recognition model, introduces the PLUS model to simulate their evolutionary pathways, and combines it with the Geographic Detector to analyze the main controlling factors and their interaction mechanisms. This achieves a shift from merely describing changes to a process of

"characteristic identification – process simulation – mechanism explanation". Based on this methodological workflow, the study preliminarily reveals that damaged space in the coastal zone exhibit strip-shaped agglomeration features and expansion trends, while the driving mechanisms demonstrate interaction enhancement effects. This provides an analytical perspective for identifying key structural units of damaged space and offers an evidence-based basis for zonal restoration guided by Nature-based Solutions.

Simultaneously, the technical framework combining the clustering recognition model and evolution simulation provides decision support for coastal landscape practices. Firstly, at the assessment level, this method can be embedded into the multi-temporal landscape data processing workflow, enabling the identification and classification of agglomeration characteristics of damaged space, thus providing data support for the refined diagnosis of coastal landscapes. Secondly, at the restoration level, by revealing the response relationship of "damage type – evolution pathway – main controlling factor", it can provide planners with a quantitative basis for determining the formation logic and evolutionary direction of different damaged units. At the governance level, combined with scenario simulation results, this framework can support the prediction of spatial evolution under different intervention intensities and restoration strategies, offering a decision-making reference for the selection of zonal restoration and management pathways.

The current research still has certain limitations. On one hand, damaged space involve not only changes in the physical environment but are also closely related to policy regulation. The driving factors selected for this study are limited to open-source data. In the future, social data could be introduced through surveys to construct the driving mechanism between landscape damage and social well-being, enabling a comprehensive analysis of the formation patterns and regulation strategies of coastal landscape damaged space. On the other hand, in terms of research scope, the current study uses the coastal zone of Yancheng City as a case. However, coastal landscape types globally are diverse, widely distributed, and significantly varied. There is an urgent need to conduct typological research on typical coastal regions, exploring the characteristics of landscape damaged space and their restoration strategies under different environmental conditions.

Using model optimization to drive precise identification, leveraging data fusion to support dynamic monitoring, and utilizing landscape resilience regulation to underpin scientific governance are important directions for the current digital and intelligent development of coastal landscapes. This study provides a demonstration pathway and methodological basis for conducting diagnosis and evolutionary analysis of damaged space via a clustering recognition model. In the future, promoting the application of this method in other types of coastal cities is expected to enable the fine characterization of coastal landscape damage patterns, providing theoretical support and practical tools for the zonal optimization and resilience enhancement of urban coastal landscape systems.

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Water Management, Hydrology and Coastal Resilience

Automating Keyline Planning for Urban Landscapes: A Computational Workflow for Water-Sensitive Design

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Abstract: Climate change intensifies urban water challenges. Although water-sensitive urban design (WSUD) offers adaptive solutions, its implementation remains fragmented at catchment scale. This study addresses the lack of catchment-scale planning by automating P. A. Yeomans' agricultural keyline planning logic into a digital terrain analysis workflow. Using the SAGA geomorphon landform classification algorithm in QGIS, the methodology was tested on the Sandy Creek sub-catchment (3.2 km²) in Brisbane, Australia, with parameters optimised at a 1000m radial limit and 0.5° threshold angle. Analysis identified 1362 hollow zones, 75 of which exceeded the 500 m² significance threshold. Land-use analysis showed that 36% of these key points were on council land and 41% were within residential parcels. Validation against five historical reservoir locations confirmed spatial alignment within 100 m of all sites. This open-source workflow provides a data-driven framework for catchment-scale storm-water management that overcomes WSUD fragmentation using terrain-informed hydrological logic.

Keywords: Keyline planning, geomorphon classification, water sensitive urban design, digital terrain analysis, catchment-scale planning

1 Introduction

Global climate change is forcing cities to adapt to increasingly extreme weather conditions. Brisbane, a subtropical city in Queensland, Australia, has a volatile history of severe floods and prolonged droughts, exacerbated by rising annual temperatures (LAZ & RAHMAN 2022). Catastrophic events, such as the 2011 and 2022 floods, underscore the city's vulnerability. These risks, coupled with a 1.7% annual population growth rate (ABS 2022), intensify the demand for resilient urban development. Since the 1990s, global approaches such as Green Infrastructure (GI) and water-sensitive urban design (WSUD) have emerged as adaptive solutions (FLETCHER et al. 2015, WONG 2006). However, Australian planning has historically relied on technocratic engineering, rather than integrated design strategies.

Despite the rise of WSUD, implementation remains fragmented. Current practice often prioritizes opportunistic factors such as land availability over hydrological logic, resulting in scattered interventions that lack catchment-level integration (KULLER et al. 2017). A primary limitation is the hidden nature of urban surface water flows. Since the advent of underground stormwater infrastructure, intrinsic water network patterns have been obscured, becoming ephemerally visible only during heavy rain. This invisibility, often manifested as lost creeks and fragmented wetlands, can lead to misguided decisions in urban planning and legislation. While LiDAR enables detailed terrain visualization at urban scales, DTM applications have been developed primarily for flood risk assessment and hydraulic modelling (MUHADI et al. 2020), leaving their potential for proactive terrain-informed design tools largely unrealized (KULLER et al. 2017).

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This research bridges this gap by adapting the P. A. Yeomans (1981)' keyline planning – an agricultural method designed to harness gravitational flow – to urban contexts through computational automation. Keyline planning begins by identifying "keypoints": strategic inflection zones where water naturally concentrates at high elevations. Yeomans (1971) argued that cities retain the hydrological logic of their landscapes, yet urban adoption has been hindered by topographic illegibility and a lack of digital tools. While widely adopted in geomorphological research, the geomorphon classification method developed by Jasiewicz and Stepinski (2013) has only recently emerged in landscape architecture, primarily for landscape character assessment (MOHAMMED et al. 2025). This study leverages this procedure to develop the first automated workflow for translating keyline principles into replicable algorithms. Computationally, keypoints were identified as the centroids of significant hollow landforms (geomorphon-classified convergent zones exceeding 500 m ²) and ranked into four tiers (Primary >10,000 m² to Quaternary 500-1,000 m²) reflecting their relative hydrological capacity.

This research addresses three objectives: translating tacit keyline knowledge into algorithmic form through an open-source GIS workflow; validating that methodology on an urban subcatchment against existing water infrastructure; and assessing implementation potential through land-use overlay to evaluate governance pathways for catchment-scale WSUD.

2 Methods

2.1 Study Area

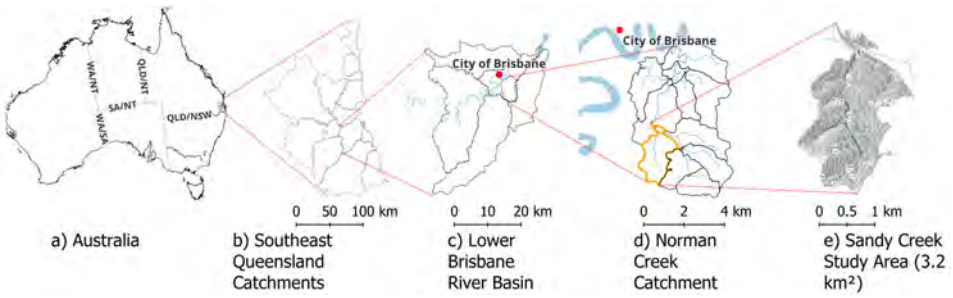

Fig. 1: Study area: Sandy Creek sub-catchment within Norman Creek catchment, Brisbane, Australia

The workflow was tested in the Sandy Creek sub-catchment (3.2 km²) in Brisbane, Queensland. This site was selected due to high-quality open-source terrain and cadastral data, existing water infrastructure for validation, and representative suburban morphology suitable for transferability. The area features established 1950s-1970s development with mixed residential, parkland, and institutional land uses. Elevation varies from 15m to 95m AHD, with terrain typical of Brisbane's suburbs.

2.2 Data Sources

Spatial datasets were projected to GDA94 / MGA Zone 56 (EPSG: 28356) using the open-source GIS software QGIS 3.44.4-Solothurn. The 5m resolution DEM from Geoscience Aus-

tralia (2015) was chosen as an optimal balance for catchment analysis; 1m resolution added too much urban noise, while 30m over-simplified landforms. Supporting datasets include cadastral boundaries, 2024-25 land-use codes, road centrelines, parks and reserves boundaries, and water infrastructure, all obtained from the Brisbane City Council Open Data (BCC 2026).

2.3 Algorithmic Approach: From Curvature to Geomorphon Classification

Although curvature-based methods (slope derivatives) were initially considered for keypoint identification, they proved to be limited owing to noise sensitivity, complex parameterization, and fixed-scale constraints. In contrast, the SAGA geomorphon algorithm (JASIEWICZ & STEPINSKI 2013) utilizes pattern recognition and the line-of-sight principle to identify landforms across adaptive spatial scales. This approach offers three advantages: self-adapting neighbourhood analysis for diverse valley geometries, a comprehensive 10-class landform map, and simplified parameterization (Radial Limit and Threshold Angle).

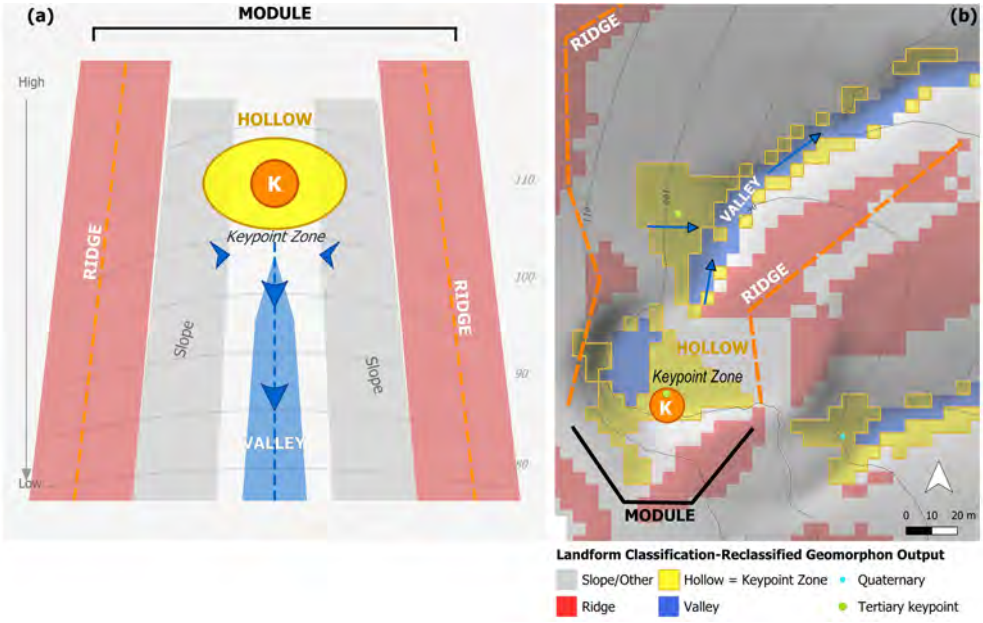

Fig. 2: Conceptual relationship between Yeomans' keyline module structure and geomorphon landform classification: (a) The traditional keyline module is defined by the main ridge, bounding primary ridges, and central valley, with a keypoint at the valley head, (b) Equivalent terrain through geomorphon classification, where hollow zones (Class 7) correspond to key point locations

The algorithm classifies terrain into ten elements: (1) flat, (2) peak, (3) ridge, (4) shoulder, (5) spur, (6) slope, (7) hollow, (8) footslope, (9) valley, and (10) pit. In keyline theory, these correspond to landscape features where ridges define module boundaries and valleys represent drainage paths. The relationship between geomorphon classification and the keyline

module structure, bounded by descending primary ridges and an ephemeral watercourse, is illustrated in Figure 2.

The keypoint occurs at the valley head, where the landform transitions from a convex to a concave geometry. This inflection zone corresponds directly to the geomorphon "hollow" (7) classification, enabling the automated identification of features that traditionally require expert field observation. The algorithm captures these geometries by analyzing elevation relationships across eight directions within the specified Radial Limit.

2.4 Parameter Optimisation

Parameter sensitivity testing followed the convergence methodology of Jasiewicz and Stepinski (2013), who recommended increasing the Radial Limit (RL) until the classification results stabilized. Four RL values (500m, 1000m, 1500m, 2000m) were tested with a constant threshold angle (TA) of 0.5° (Fig. 3).

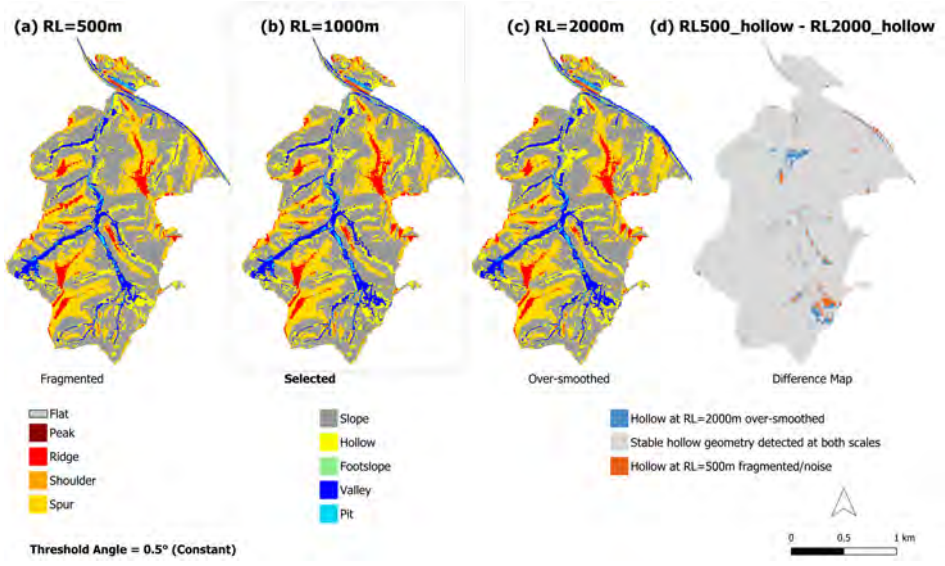

Fig. 3: Parameter sensitivity analysis: (a) RL=500m produces fragmented landform networks with excessive local variation, (b) RL=1000m (selected) provides coherent catchment-scale hollow zones, (c) RL=2000m over-smooths topographic detail, merging distinct hollow zones, (d) Difference map (RL=500m minus RL=2000m): orange cells indicate hollows detected only at a small scale (fragmentation noise); blue cells indicate hollows detected only at a large scale (over-smoothing); grey indicates spatial agreement. Disagreement concentrates on minor features, confirming methodological robustness at RL=1000m. Threshold Angle=0.5° constant.

At RL=500m, classification produced fragmented networks with excessive local variation that were unsuitable for catchment-scale analysis. At RL=1000m, coherent landform patterns emerged with continuous ridge networks and well-defined hollow zones. At RL=1500m, the

standard benchmark from Jasiewicz and Stepinski (2013), equivalent to 50 cells at 30m resolution, the results were visually similar to RL=1000m, confirming parameter convergence. At RL=2000m, the topographic detail was over-smoothed, merging distinct hollow zones. RL=1000m was chosen for capturing coherent catchment-scale features with minimal computational cost. The similarity between RL=1000m and RL=1500m validates this choice against the established methodology.

2.5 Keypoint Extraction Workflow

A seven-step extraction workflow was implemented using the QGIS Graphical Modeller (Fig. 4). The complete automated workflow, including the Python processing script and standard styling files, is available as open-source software (TERRAGEO 2026). Unlike algorithms that require hydrologically filled DEMs, geomorphon classification uses raw elevation data to analyze the actual surface morphology. The process includes: (1) classification using optimized parameters; (2) isolating hollow zones (Class 7); (3) vectorization; (4) area calculation; (5) filtering polygons exceeding 500 m²; (6) generating centroids as keypoint locations; and (7) hierarchical classification (Primary >10,000 m² to Quaternary 500-1,000 m²). The 500 m² threshold was pragmatically established through iterative testing to balance feature preservation with artifact exclusion and corresponds to the minimum footprint of parkland bioretention systems in the Southeast Queensland design guidance (WATER BY DESIGN 2014), providing a practical lower bound for catchment-scale WSUD interventions. Finally, keypoints were intersected with land-use data and compared against existing reservoir locations via proximity analysis. Spatial validation was conducted using a Monte Carlo simulation (n=1,000 iterations) implemented in Python via the QGIS integrated console, randomly generating 75 points within the catchment boundary at each iteration and calculating the median distance to the five reservoir locations. The simulation script is available in the project repository (TERRAGEO 2026).

Fig. 4: Keypoint extraction via a seven-step workflow in the QGIS Graphical Modeller.

3 Results

Geomorphon analysis identified 1,362 hollow zones across the catchment, of which 75 exceeded the 500 m² significance threshold (Tab. 1). These were classified into four tiers based on the hollow area: Primary (>10,000 m², n=5), Secondary (5,000-10,000 m², n=7), Tertiary (1,000-5,000 m², n=37), and Quaternary (500-1,000 m², n=26). The 1,287 hollow zones be-

low 500 m² were excluded from the primary analysis but retained for the infrastructure overlay assessment. While the computational method lacks the nuance of expert field observation, automated analysis identified 95 keypoints, a 26% increase over the 75 keypoints identified in manual pilot studies. This higher sensitivity is attributed to the script's rigorous enforcement of square-pixel geometry and the use of a 4-connected topology during preprocessing, which successfully resolved complex hollow clusters into distinct hydrological units often aggregated by manual methods.

Table 1: Distribution of significant keypoints (n=75) by hollow area class and land use context in the Sandy Creek sub-catchment.

Size Class	Road Infra.	Parks/ Reserves	Residential	Institutional	Other	Total
Primary (>10,000 m²)	2	0	3	0	0	5
Secondary (5,000-10,000 m²)	5	0	2	0	0	7
Tertiary (1,000-5,000 m²)	8	4	16	3	6	37
Quaternary (500-1,000 m²)	1	7	10	4	4	26
Other (<500 m²)	170	298	438	57	324	1287
Significant Total (>500 m²)	16	11	31	7	10	75
Grand Total	**186**	**309**	**469**	**64**	**334**	**1362**

Overlay analysis with land-use data revealed distinct spatial patterns across size classes (Tab. 1). Residential land accounts for the largest share, with 31 keypoints (41%) on private parcels. Road infrastructure accounts for 16 keypoints (21%), parks and reserves for 11 (15%), and seven are on institutional land, such as schools and sports facilities. The remaining 10 are in commercial, vacant, and mixed-use parcels. Council-controlled land (roads and parks) has 27 keypoints (36%), sites ready for implementation without private land negotiation. Larger keypoints are concentrated along roads: seven of the 12 Primary and Secondary points are on or near roads, which often follow natural drainage paths. In addition to the 75 significant keypoints, 186 hollow zones coincide with roads, including 53 at intersections, offering opportunities for streetscape interventions such as rain gardens and bioswales (WATER BY DESIGN 2014).

To determine if computational keypoint detection aligns with historical engineering choices, 75 keypoints and all 1,362 hollow zone centroids were compared to five potable water reservoirs in the study catchment (Fig. 5). Built between the 1950s and the 1970s, these reservoirs reflect siting decisions made before the advent of digital terrain analysis. All five are within 100 m of an algorithm-identified hollow zone. Although this small sample limits broad conclusions, the 100% spatial match – despite three sites being below significance – confirms that the algorithm detects terrain features where mid-century engineers chose to locate water. The Toohey reservoirs corresponded with significant keypoints at 18.38m and 36.79m, within the 5m DEM resolution uncertainty. The other three, Wellers Hill No. 1 (52.53m), Tarragindi (67.00m), and Wellers Hill No. 2 (87.16m), aligned with smaller hollow zones of 5m² and 15m² below the 500m² significance threshold.

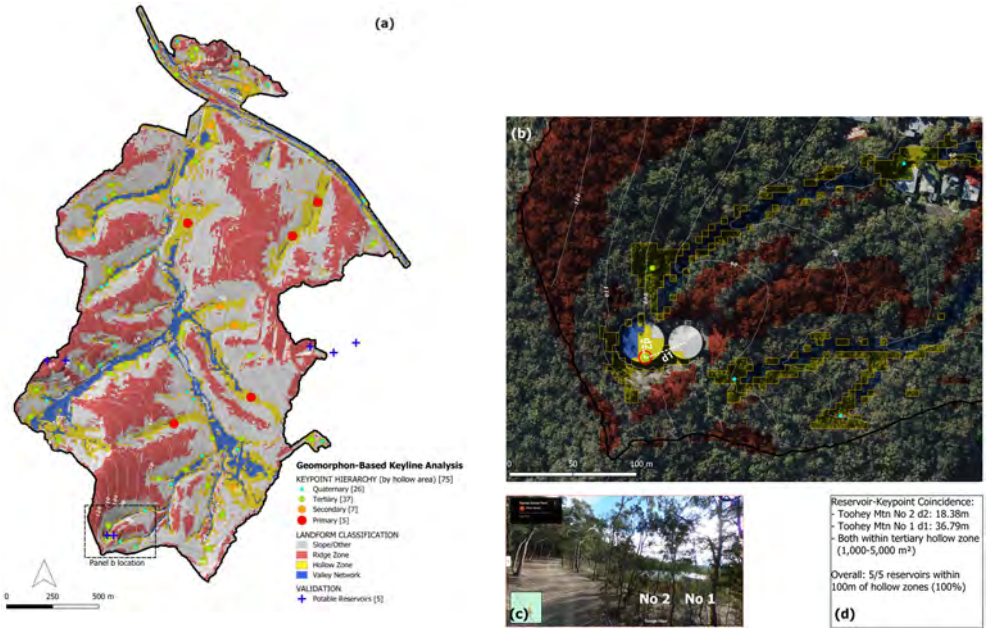

Fig. 5: Validation of keypoint locations against historical water infrastructure in the Sandy Creek sub-catchment: (a) Catchment overview: significant keypoints (n=75) classified by hollow zone area overlaid on geomorphon landform classification; five potable reservoirs (1950s-1970s) shown as blue crosses, (b) Toohey Mountain detail: Toohey No. 1 and No. 2 reservoirs located 36.79m and 18.38m from an algorithmically identified secondary keypoint; remaining three reservoirs (Wellers Hill No. 1, 52.53m; Tarragindi, 67.0m; Wellers Hill No. 2, 87.16m) aligned with sub-threshold hollow zones below the 500 m² filter, (c) Toohey Mountain reservoir infrastructure (Google Street View 2018). All five reservoirs fall within 100m of algorithmically-identified hollow zones.

The algorithm correctly identified hollow landforms at all five reservoir locations, but only two of these hollows passed the significance filter. The other three were excluded as they were too small, even though engineers had previously considered those locations suitable for water infrastructure. While keyline planning targets surface water management rather than potable storage, both require convergent landforms where water concentrates at high elevations. This suggests that the 500 m² threshold, although useful for dataset management, may overlook viable locations for infrastructure.

A Monte Carlo simulation (n=1,000) was used to test whether this spatial alignment exceeded random chance. The result was not statistically significant (p=0.31), reflecting a structural scale mismatch: keypoints concentrated in valley-head positions, whereas potable reservoirs occupied high-catchment ridge-proximate sites, producing a spatial separation that limited distance-based comparison. The median offset of 95.3m nonetheless represents a 27% improvement over the random median of 130.6m. The convergence of hollow geometry across

all five reservoir locations confirms that the algorithm identifies terrain features independently, which was recognised through pre-digital engineering judgment as optimal water concentration zones.

4 Discussion

Kuller et al. (2017) found that WSUD placement in Melbourne was largely opportunistic rather than hydrological; a pattern mirrored in Brisbane. This computational workflow shifts the focus from existing site constraints to natural water concentration, leading to distinct spatial outcomes. The 27 keypoints identified on council land represent the most actionable findings for public works. Sixteen sites within road reserves were aligned with the existing municipal stormwater management. In contrast, the 31 residential keypoints pose implementation challenges, such as rate rebates or subsidized rain garden installations.

Terrain-informed placement prioritizes efficiency, leveraging gravitational flow to maximize water interception per unit of investment. Although this study did not include hydraulic modeling, this efficiency claim remains a compelling hypothesis to be tested through future hydrological simulations. Beyond individual site identification, keypoints function as nodes within a latent catchment network. Unlike geomorphon pits, which are closed depressions removed during hydrological preprocessing, keypoints are inflection zones that intercept and laterally redistribute valley flow toward ridges, connecting landscape units rather than terminating flow. This logic, originally applied by Yeomans to gravity-fed irrigation, now guides the development of urban blue-green infrastructure. These 75 keypoints serve as anchors for basins and wetlands, providing the geometric foundation for a catchment-scale planning framework that the author is actively developing.

Yeomans' principles traditionally require extensive field experience. The geomorphon approach computationally encodes tacit knowledge by identifying convergent terrain cells that align with Yeomans' keypoint concept, confirming their applicability within this catchment. Although the computational method lacks the nuance of expert field observations, such as soil and vegetation patterns, it ensures repeatability, scalability, and accessibility for non-specialists. This approach is defensible for broad catchment-scale planning, though field verification remains vital for site-specific designs.

The interpretation of these results is subject to several limitations. The 500 m² threshold, derived from iterative testing rather than hydrological modelling, may vary across different terrains; future calibration through hydraulic performance modelling against established sizing guidance (WATER BY DESIGN 2014, 2017) is recommended. Additionally, the 5m DEM resolution smooths the micro-topographic features essential for site-scale design. Environmental variables like soil permeability and groundwater fall outside the study scope, while urban complexities such as utilities and heritage constraints require manual assessment beyond the automated workflow. Validation across five reservoir locations represents a small sample size, and multi-catchment testing remains a priority for future research.

5 Conclusion and Outlook

This research fulfilled three objectives: encoding tacit keyline knowledge, validating the methodology, and assessing implementation potential. The geomorphon-based workflow successfully replicated Yeomans' keypoint geometry, offering a reproducible method for non-specialists. Validation against existing reservoirs confirmed that computational analysis aligns with expert engineering logic, as all five reservoirs matched algorithmically identified hollows. Implementation analysis revealed distinct pathways: 36% of keypoints reside on council land for public works, while 41% on residential land suggests incentive-based strategies. Future research should focus on field validation, hydrological modelling, and network-scale integration, establishing a systematic foundation for terrain-informed, water-sensitive urban design.

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Flood Simulation in Design-Test Loop: An Integration with Evidence-Informed Landscape Design Iteration

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Abstract: Improving urban flood resilience requires design tools that integrate hydrodynamic evidence with iterative spatial design. Current practice separates terrain modelling and flood analysis into decoupled platforms, limiting design flexibility and responsiveness. This study proposes an iterative design approach that couples real-time terrain manipulation and flood simulation in Unreal Engine with hydrodynamic validation in MIKE+. Tested within developed floodplain along Melbourne's Maribyrnong River, the approach enables rapid feedback of creative exploration to inform flood adaptation design iteration while retaining evidential reliability, demonstrating how flood simulation can incorporate evidence-informed landscape design.

Keywords: Flood adaptation, simulation, design-test iteration, game engine

1 Introduction

Flooding is a growing global concern, intensified by climate change impact and rapid urbanization (HEGGER et al. 2013, POTTIER et al. 2005). Along many urban waterways, development and hard surfaces accelerate runoff and constrains flow, diminishing the landscape's natural capacity to convey and store water.

In the state of Victoria, this sequence is vividly illustrated along the Maribyrnong River, one of Melbourne's most urbanised waterways. The Kensington Banks precinct (Melbourne, Australia), developed as a housing estate in the late 1990s, considered at the time, safe from flooding from the adjacent Maribyrnong River. That perception shifted in October 2022, when prolonged rainfall caused the Maribyrnong to reach its highest level in nearly half a century, inundating more than 500 properties across the lower catchment (Maribyrnong City Council 2024). Subsequent hydraulic re-assessment placed nearly 900 homes within the 1 % annual-exceedance flood zone (Melbourne Water 2024).

That unprecedented flood, and the subsequent evolution of hydrodynamic modelling techniques that recognise changing rainfall patterns, is overturning planning assumptions, and damaging public trust. There is a clear need for both resilience planning but also ways to test different options for its format with the communities who currently and are expected to reside there in the future.

In the present case study, Melbourne Water's published flood extent map provides valuable insight into baseline vulnerability but remains distant from supporting future-casting explorations. This surfaces a disconnection between conceptual flood adaptation in design approach and the tools available to evaluate them, raising the critical questions of the present study: How can flood modelling better inform and support design of the flood-resilient landscape in terms of a better understanding of where, when, and how water interacts with land-

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scape form? How can scenario-based simulation be integrated into a design approach as a responsive tool that is accessible for creative exploration and rigorous enough to inform site-specific flood adaptation?

Addressing the above questions motivates the investigation of an iterative design approach. The present study integrates real-time flood simulation (Unreal Engine) and engineering hydrodynamic modelling (MIKE+) within a design-test loop. Using a projected 1% AEP (2100) flood scenario as the design driver, this approach supports rapid spatial iteration and refinement of terrain-based adaptation strategies, with final performance verified through MIKE+.

2 State of the Art

Previous studies in flood risk analysis have seen terrain as a critical component (BIRON et al. 2014, LANE 2017, MING et al. 2025, PALAZZO & WANG 2022, ROGERS et al. 2020).This is embedded in flood adaptation in landscape architecture's terrain-based strategies that manipulate ground form to manage water storage, conveyance, and delay, carried by concepts such as multifunctional floodplains. However, early-stage design still struggles to test whether and how landform manipulations may alter flood behaviour at the intervention scale.

Typical design tools for terrain manipulation such as Rhino, Civil 3D, 3dsMax, lack physically based hydrodynamic computation. While water effects can be represented through rising planes or particle-based plugins, these are focused on visual fidelity, offering limited capacity to test design exploration regarding to inundation depth, velocity and time stamp. This makes these programs useful for communication, but their accuracy is not verifiable for actual flood impact.

Conversely, engineering hydrodynamic models such as MIKE+, TUFLOW, and HEC-RAS 2D deliver authoritative predictions of depth and velocity but demand extensive data preparation, calibration, and computational resources, restricting their use in rapid design iteration (NÉELZ & PENDER 2009, YIN et al. 2024). This represents a technical gap between analytical accuracy and design agility.

Recent advances in GPU-based game engines such as Unreal Engine and Unity begin to bridge this divide by integrating lightweight shallow-water solvers with immersive visualization (OZTURK et al. 2025, YIN et al. 2024). These prototypes reveal the potential for design-oriented flood simulation, opening a middle ground that couples analytical credibility with the immediacy and spatial intuition required for landscape design. Within Unreal Engine 5, this potential is strengthened through its Landscape Mode which enables direct topographic sculpting, and the built-in plugins for real-time flood simulation. This combination allows designers to prototype terrain interventions interactively.

Positioned between engineering hydrodynamic models and game-engine environments, the present study explores how coupled model can be leveraged through a design-oriented method. Rather than replacing engineering software with a new platform, the study demonstrates a transformative methodology for iterative, evidence-informed design exploration within flood-resilient urban landscape.

3 Methods and Results

3.1 Study Area and Material

This research focuses on a case study within Kensington Banks at urban-block scale, where a cluster of urban blocks situates on the lower floodplain of the Maribyrnong River in Melbourne's north-west (Fig. 1). The river meanders through urbanised floodplain before reaching the Kensington Banks precinct, the selected case study site for this research. This area exemplifies the complexities of medium-density residential blocks in urbanised floodplains and was significantly impacted during the October 2022 flood event. Within the selected modelling domain (Fig. 2), building footprints and road casement account for approximately 31.5% and 23.3% of area, respectively.

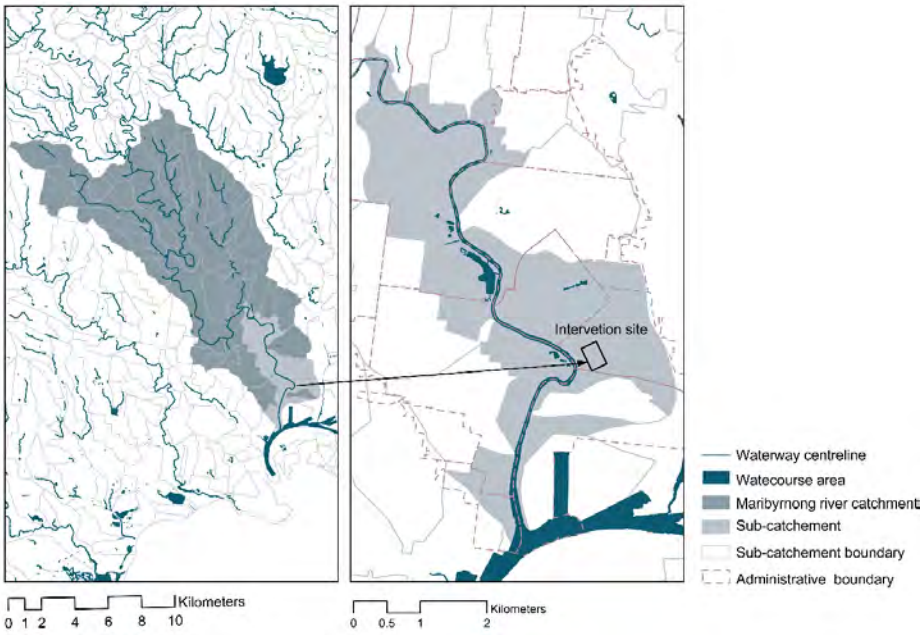

Fig. 1: Maps showing Maribyrnong river catchment (left) and the sub-catchment inclusive of the intervention site of the present study (right)

Regarding to this context, the present design approach connects GIS, design-oriented simulation, and hydrodynamic model in a nested manner. Initial data inputs prepared a 2 × 2 km terrain domain, which was extracted from 1 m LiDAR-derived DEM data within ArcGIS Pro, to preserve buffer for hydrodynamic modelling. Additional data inputs prepared for hydrodynamic modelling included water area polygon from Melbourne Water shapefiles and a spatial roughness raster created using land-use-based Manning's n values (Engineers Australia 2019, Fig. 2).

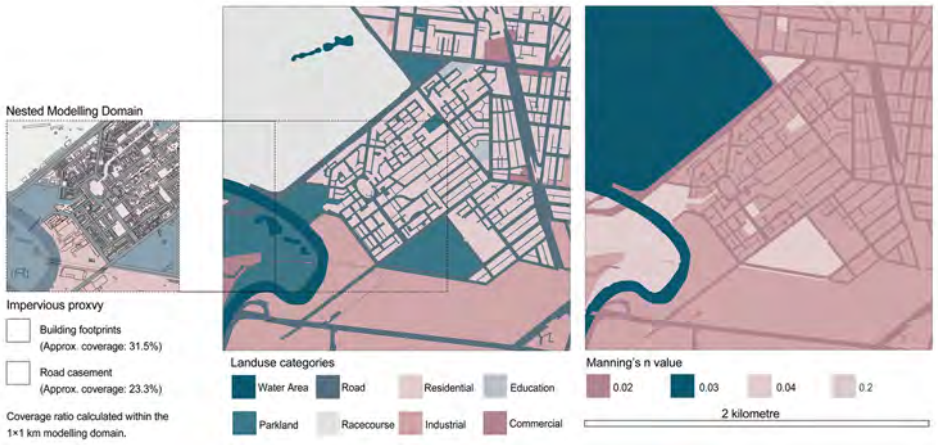

Fig. 2: Nested model domain and map showing watercourse area and landuse zoning (left); and derived Manning's roughness coefficient map, using parameters adapted from ARR2019 (right). Data sources: Vicmap Planning; Melbourne Water; Manning's n adapted from ARR2019 (Engineers Australia 2019).

The 1 × 1 km modelling domain was adopted to capture the upstream river reach and lateral floodplain context governing local inundation. Within this extent, a smaller sub-domain comprising residential blocks was identified as the intervention site with attempts to maintain high resolution while focusing computational resources on understanding of the local flood behaviour.

This nested domain structure is widely adopted in published study on urban flood modelling with MIKE FLOOD and other multi-scale studies to preserve hydraulic gradients and minimise boundary effects (HARTNETT & NASH 2017, MING et al. 2025, ZHAO et al. 2021), and is here adapted to support iterative design exploration under consistent riverine flood drivers (MUKHERJEE et al. 2025).

3.2 Baseline Hydrodynamic Model

Based on the nested manner, a 1D River-2D Overland Flow coupled hydrodynamic model was constructed as a reference to understand flow behaviour across the site.

In the MIKE+ model, a 2D domain was established based on the DEM of 1 x 1 km extent. Upstream flow enters the site through a 1D-2D coupled river reach, with boundary hydrographs scaled to the 1% AEP scenario. Floodwaters then propagate across the 2D domain floodplain according to topographic gradients and roughness, reflecting standard hydrodynamic practice in which the DEM governs flow paths.

Boundary conditions adopted a hydrograph derived from the Maribyrnong gauge, scaled to reach the 1 % AEP peak discharge of 915 $m^3 s^{-1}$ reported by Melbourne Water (Fig. 3). The scaling assumed shape invariance of the hydrograph, consistent with established methods for design-flood derivation (PETERS-LIDARD et al. 2017).

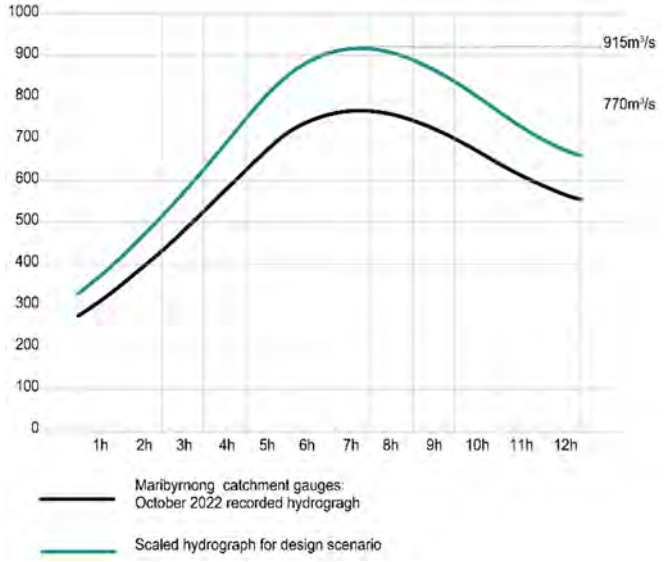

Fig. 3: Measured hydrograph from the Maribyrnong River gauge during the October 2022 flood event (black line), and scaled design hydrograph for the 1% AEP climate change scenario (green line). The scaling factor (770 → 915 $m^3 s^{-1}$) was applied under the assumption of hydrograph shape invariance, due to limited availability of full time-series design flows. Data source: Melbourne Water.

3.3 Unreal Engine Flood Simulation and Baseline Alignment

A simulation environment of identical spatial extent was created in Unreal Engine5.6, using the resampled DEM as heightmap (PNG format) to generate existing terrain, representing upstream slopes, channel alignments, and floodplain depressions consistent with the hydrodynamic model. Within this environment, the nesting approach was applied to maintain comparability across scenarios with the fixed parent domain and terrain interventions limited to selected residential blocks.

Baseline alignment between Unreal Engine and MIKE+ focused on inundation extent as a target. Maribyrnong River segment adjacent to the intervention area was simplified and represented by built-in 'water body river' in Unreal Engine. This spline-based river segment in this study is controlled as floodwater source via water parameter including depth and river width, supervised by Shallow Water River Actor under Niagara Fluids, a built-in plugin facilitated with simplified Shallow-Water template (Niagara Fluids Reference Guide, Epic Games). The MIKE+ model provided initial reference for depth parameter, which was adjusted until the flood extent at the event peak visually align with/match/reproduce the MIKE+ output and Melbourne Water's published flood extent (Fig. 4), thus establishing a reliable foundation for subsequent design testing.

The following flood simulations (Fig. 5) were then performed over the altered UE terrain with constant water body river for all intervention iterations. This enables differences in inundation patterns to be attributed specifically to altered terrain within the intervention site, helping maintain comparability and simulation alignment.

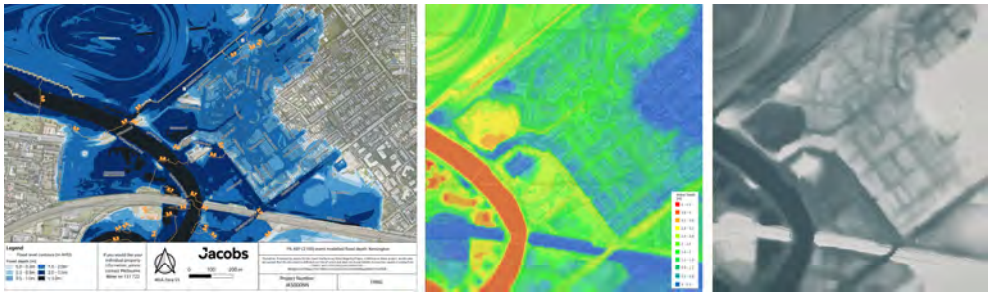

Fig. 4: Comparison between (left to right), Melbourne Water's projected 1% AEP flood extent map, MIKE+ result map and screenshot of Unreal Engine baseline simulation Data Source: Melbourne Water

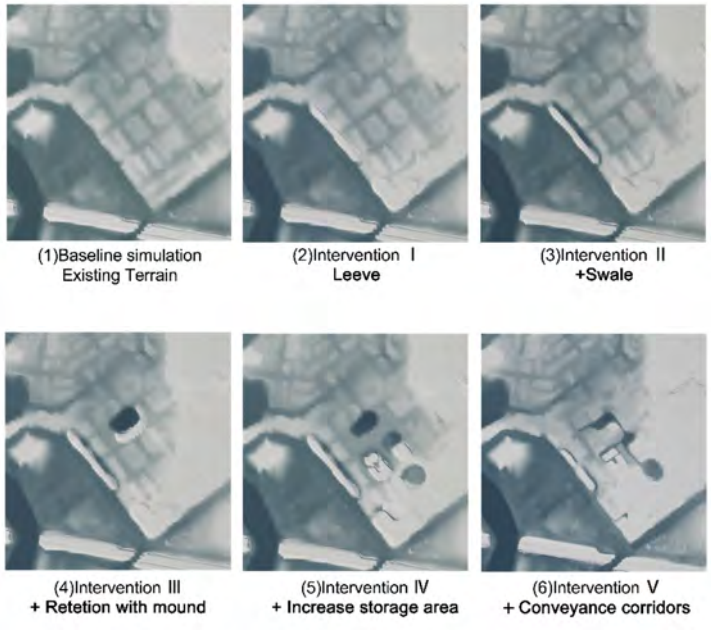

Fig. 5: (1) Baseline simulation of existing terrain and (2-6) a series of iterative simulations showing creative exploration of terrain interventions

3.4 Final Hydrodynamic Verification

The altered terrain from the final Unreal Engine iteration was exported as a 16-bit heightmap, re-georeferenced and formatted within ArcGIS correctly before re-articulating to hydrodynamic testing within MIKE+ (Fig. 6). This allowed a visibly explicit comparison between the game-engine simulation and the engineering hydrodynamic model while holding flood drivers constant.

This testing was conducted with an attempt to get quantifiable output that indicates the extent to which conceptual design prototypes effect flood behaviour, however, examination of full numerical correspondence is out of the scope of this study. Therefore, this verification step evaluates whether the Unreal Engine simulation sufficiently informs flood-resilient landscape design exploration, such as inundation extent, flow routing patterns, and the response of floodplain connectivity.

The close alignment observed between UE and MIKE+ in these indicators (Fig. 6) confirms that the game engine environment provides acceptably reliable hydrodynamic feedback to support iterative terrain intervention at early stage. MIKE+ is then used to quantify performance outcomes only at the final intervention stage, as detailed in the next section.

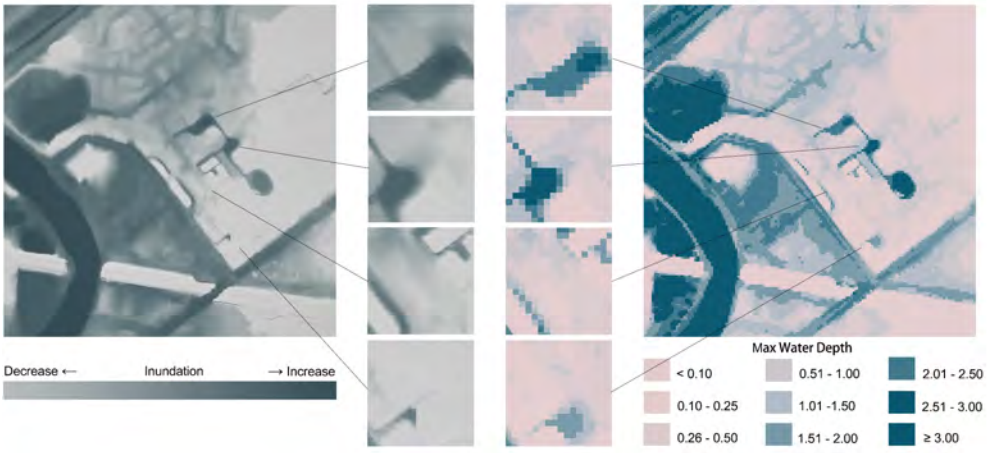

Fig. 6: Comparison of the real-time flood simulation within Unreal Engine (left) and the hydrodynamic model through MIKE+ (right). Both are based on the altered terrain incorporating low-lying storage pockets and adjusted conveyance corridors.

Iterative simulations within Unreal Engine provides immediate feedback on inundation extent and flow behaviour, supporting design decisions by revealing when and where floodwater interacts with modified topography. Following processive refinement, the final terrain configuration was re-simulated in MIKE+ to quantify performance outcomes. Results indicate flood-depth reductions of approximately 0.20-0.45 m within target blocks where storage pockets and conveyance corridors were introduced (Fig. 7).

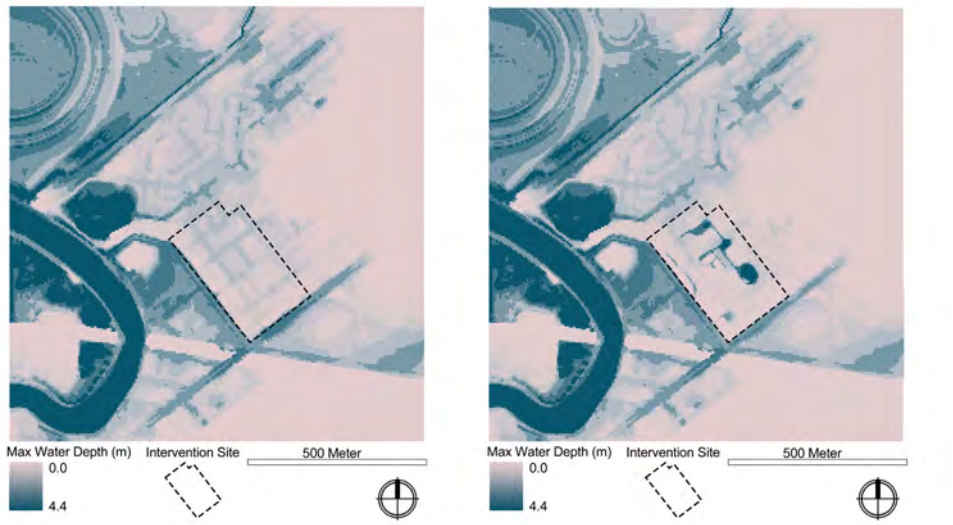

Fig. 7: Comparison of maximum water depth maps conducted within MIKE+ indicates the decrease of inundation within the targeted area. The results are based on existing terrain (left) and altered terrain(right) from the final iteration in Unreal Engine.

4 Discussion and Conclusions

The Kensington Banks case study shows how coupling Unreal Engine and MIKE+ forms an iterative design-test loop: terrain changes are modelled in Unreal, validated in MIKE+, and refined through successive runs. In this way, the loop connects speculative design exploration with hydrodynamic evidence, allowing flood-adaptation concepts to be tested at the urban-block scale. This approach enables rapid scenario testing and visualisation of flood onset, propagation, and recession – temporal behaviours that conventional maps cannot convey. The validation step is not MIKE+-specific and could be replicated using other 2D solvers capable of producing comparable depth/extent outputs (e. g., HEC-RAS 2D).

However, although Unreal Engine closely reproduces MIKE+ inundation extents and flow pathways, it does not provide georeferenced depth fields for pixel-level validation. As a result, verification in this study is limited to visual extent and pattern-based correspondence, which is appropriate for design stages that prioritise rapid visualisation and iteration. This study does not claim that Unreal Engine alone is sufficient for flood testing. Suitability of the present approach would depend on site-specific context, intended use, and required accuracy, and should be tested explicitly across varied conditions and design scenarios.

Future work could address the lack of georeferenced depth outputs in Unreal Engine by developing a GPU-to-raster depth extraction interface, enabling full metric alignment between platforms and extending the workflow toward engineering-grade optimisation.

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Geoinformation Maintenance of Small Rivers for Their Restoration: A Case Study in Vinnytsia City, Ukraine

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Abstract: Small rivers play a crucial role in urban ecological and climate resilience by providing natural drainage, regulating microclimates, and supporting biodiversity. In Ukrainian cities, these rivers are often neglected, leading to degradation, loss of riparian zones, and reduced ecosystem services. In Vinnytsia, climate change has intensified these risks: heatwave events have doubled, and annual precipitation has decreased by 13%, threatening watercourses, vegetation, and urban microclimates. This study developed a GIS-based methodology that involved inventorying rivers, collecting volunteer and official geospatial data, creating a geodatabase, modelling networks, and visualising data in ArcGIS Online. The results document 167.48 km of river network, highlight accessibility and pollution issues, and provide evidence for conservation. The GIS application provides a tool for monitoring, restoring, and integrating small rivers into urban planning, promoting sustainable, nature-based solutions for Vinnytsia. In the future, plans are underway to revitalise and restore small rivers, using nature-based methods while ensuring accessibility for all citizens.

Keywords: Small river network, urban area, geospatial analysis, volunteered GIS, GIS application

1 Introduction

Urban watercourses are freshwater sources and critical components of cities' blue and green infrastructure, playing a key role in supporting their environmental sustainability and adaptation to climate change (DINIĆ-BRANKOVIĆ & MARKOVIĆ 2021). However, human activities, particularly increased urbanisation, are destroying natural conditions and posing a serious threat to biodiversity in freshwater bodies. Successful experience with environmental protection measures demonstrates that mitigating urban stressors through revitalisation and water-quality improvements significantly increases biodiversity and ecological functioning in urban watercourses. Therefore, the use of GIS enables the integration of all available geospatial and semantic data, thereby supporting optimal spatial planning for urbanised areas, while accounting for rational land use and the preservation of freshwater ecosystems from overdevelopment (KOBOJEK 2017, NAWIEŚNIAK-CAESAR et al. 2019, LANGIE & RYBAK-NIEDZIÓŁKA 2021, SHAW 2021, CHROMÍKOVÁ et al. 2023, STIEGER & MCKENZIE 2024, SRETOVIC BRKOVIC & DJUKIC 2024). Preserving and restoring the natural characteristics of these water bodies (renaturalisation) is a priority for creating sustainable cities (ZINGRAFF-HAMED et al. 2017, RAIMONDI et al. 2020, LESPEZ et al. 2025).

In Ukraine, this problem is exacerbated by a systemic lack of official, relevant, accurate, and unified geospatial data, as evidenced by a 2021 analysis of the state of development of the national spatial data infrastructure conducted using the IGIF Methodology. Existing data on the hydrographic network are not interoperable because they vary in origin, relevance, and

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accuracy at the local and national levels (KRELSHTEYN & DUBNYTSKA 2017, KARPINSKYI et al. 2021), thereby hindering accurate spatial planning and monitoring (HOPKINS et al. 2025). As a result, in most Ukrainian cities, valuable aquatic ecosystems, especially small rivers, remain “invisible” in urban planning, leading to uncontrolled littering, disruption of the hydrological regime, and loss of critical riparian buffer zones.

In Vinnytsia (central Ukraine), where there has been an increase in the number of heatwaves and a decrease in annual precipitation (about 13%) over the past decade (RESTART AGENCY 2023), the problem of water conservation is becoming particularly acute because the river network within the municipality is in a critical state, on the verge of disappearing due to massive pollution from household, construction, and chemical waste, and to disruptions of its hydrological regime and of ecosystems and biodiversity. The Small Rivers project, implemented by the Institute of Urban Development of the Vinnytsia City Council, has identified more than 64 watercourses totalling over 110 km within the community. Until 2023, their status and the accuracy of their cartographic basis were the subject of discussion. The last study revealed a complete lack of verified spatial data on the exact locations of the riverbeds, their accessibility, and the condition of the surrounding areas (HUDZEVYCH 2023). It was this lack of a unified, comprehensive geospatial database that prevented assessing the extent of environmental degradation, identifying pollution sources, and scientifically justifying restoration measures.

The purpose of this article is to develop a methodology for inventorying small rivers in the Vinnytsia community based on a geographic information system (GIS) and to present the results obtained. This research demonstrates how a practical mapping project, which combined volunteered geographic information (VGI) with official data, provides the necessary evidence base for urban climate resilience and for integrating water ecosystems into urban planning. Thus, the article analyses the project's results as a precedent for modernising hydrographic data through community involvement and geospatial modelling.

2 Methodology of Researching

The methodology applied in this work is based on a practical geoinformation approach to the inventory and monitoring of small rivers in an urban environment. The framework integrates three key components: official geospatial data, volunteered geographic information (VGI) collected during the 'Mapping Small Rivers' project, and GIS-modelling. This approach was designed to be reproducible, providing a reliable tool for water ecosystem restoration and long-term data maintenance.

Unlike one-off mapping of territories, the proposed approach focuses on creating a geoinformation support system that enables regular data updating and accumulation, conducting observations, and integrating results into urban planning processes. The general logic of the study includes the stages of data inventory, collection of field information with the involvement of the active public using the Map Marker mobile application, standardisation and harmonisation of heterogeneous data sets, development and filling of a geospatial database of the small river network, performance of geospatial analysis, and publication of results in open data formats (GeoPackage and GeoJSON) and in the GIS application “Small Rivers of the Vinnytsia Community” based on ArcGIS Online (Fig. 1).

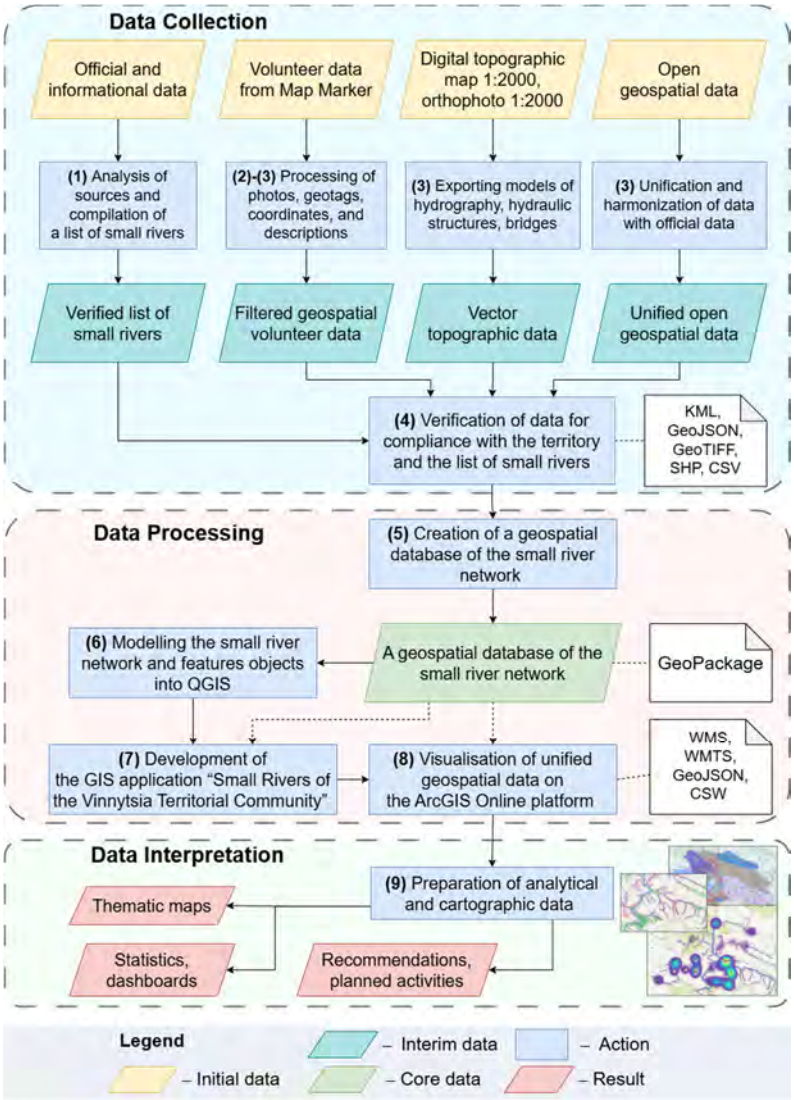

Fig. 1: The methodology schema of geoinformation modelling of the hydrographic network of small rivers in the Vinnytsia municipality (Performed by the authors)

2.1 Data Collection

The official geospatial datasets and open data sources were used as input data and reference materials, such as: orthophotomap of Vinnytsia, scale 1:2000 (2019); topographic plan of Vinnytsia, scale 1:2000 (2013); river Basin Management Plan of the Southern Bug for 2025-2030; thematic cartographic schemes provided by the NGO "Small Rivers of Vinnytsia"; approved Concept for the Development of Small Rivers until 2035; Emerald Network data;

local urban planning documentation; historical cartographic materials; OpenStreetMap data; and iNaturalist platform datasets.

One of the main tasks was accomplished through the direct participation of citizens and volunteers, who collected up-to-date data on urban landscapes, small rivers, and other obstacles along the shoreline of hydrographic features using the MapMaker application (Fig. 2). Each observation of small rivers was accompanied by photographs and structured attribute data, which were filled in according to the instructions. Photographic materials were primarily used for visual verification and confirmation of the situation through field observations, while attribute data and geolocation were used for geospatial analytics. The volunteers' observations were analysed based on the processed images and classified according to predefined attribute domain values (e. g. accessibility level, presence of waste, physical barriers). High-quality and verified photographs served as visual verification of attribute coding. A significant limitation at this stage was the manual verification of photographs. This approach enabled the analysis of the physical accessibility, protection status, cleanliness, openness, and overall availability of the river network within the Vinnytsia community.

Fig. 2: Examples of photos collected by volunteers (Photo gallery of all rivers here: https://surl.li/auhdfv)

2.2 Data Processing

In total, volunteers collected 1062 point objects, 235 linear objects, and 368 polygonal objects. Before integrating the datasets into a seamless geospatial database, the volunteer data was filtered and unified, as the valuable information was the identification of features and their detailed description. When river data were available in multiple datasets simultaneously, the features' geometries were harmonised to the official topographic plan at a scale of 1:2000, and the attribute data were refined using volunteer data and, in some cases, OpenStreetMap data. A group of 30 volunteers also identified several new segments of watercourses that had not been documented and incorporated them into the hydrographic network model.

The study results were processed using QGIS tools and published as an open-access resource on the ArcGIS Online platform (Fig. 3): https://sites.google.com/view/vinsmallrivers/. These results enabled the creation of a comprehensive geospatial database of small rivers in the Vinnytsia community for the first time. The datasets created as part of the project “Mapping the Small Rivers of Vinnytsia Community for Conservation and Sustainable Management”

were published as an open-access resource for Zenodo (https://doi.org/10.5281/zenodo.17816428). While the dataset was published on Zenodo, this article focuses on the methodological framework of combining volunteered geographic information (VGI) to verify and update official hydrographic records in a data-scarce environment.

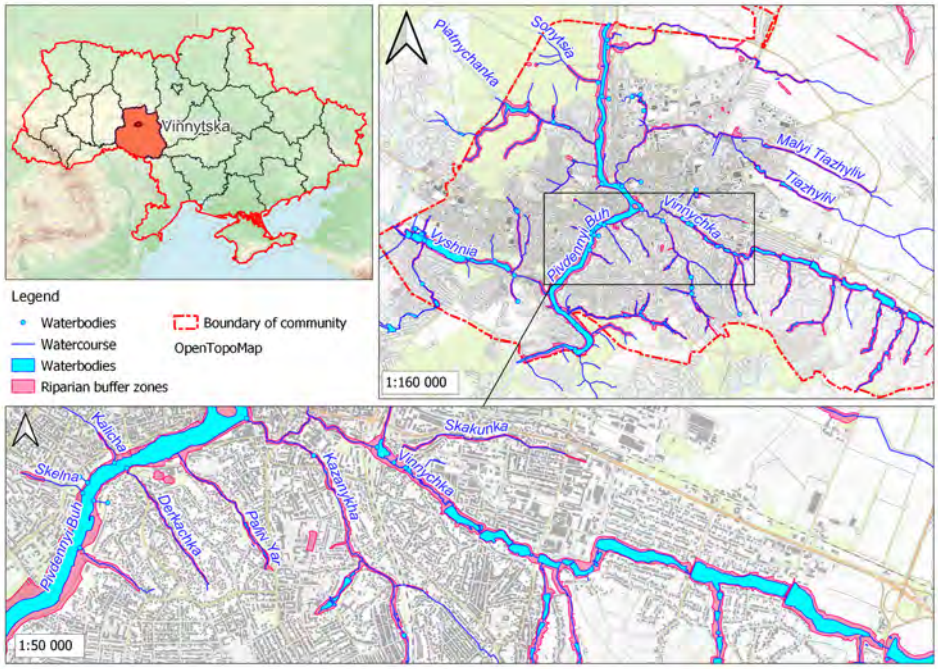

Fig. 3: Research area with examples of objects in the created hydrographic network and existing riparian zones (Performed by the authors)

3 Results

The geospatial database on small rivers in the Vinnytsia community consists of 23 feature classes, the main ones being: watercourses, hydrotechnical structures, river basins, barriers and fences, invasive plants, waste and pollution, recreational objects, bridges, vegetation, animals, volunteer tracks, coastlines, self-occupied territories, and relief. This database also contains topological line-node models of the hydrographic network. Specialists will continuously update the geospatial database developed. The NGO "Small Rivers of Vinnytsia" will operate based on up-to-date data for the geoinformation system for small rivers. The functionality of this system enables the creation of new data, the updating of existing data, and the performance of analyses based on these data. These data will be integrated into the State Water Cadastre of Ukraine to update the cadastre and share official data at the local, regional, and national levels. The total length of the river network, including the section of the Southern Bug River (Pivdennyi Buh River) within the city limits (approximately 16.5 km), is 172.91 km, of which 20.27 km is in collectors and 152.64 km is open waterways. Only 55%

(94.76 km) of the coastline is accessible for recreation or monitoring, while urban territories and manmade barriers block 78.15 km. The geospatial data show 1.78 hectares of illegal waste dumps and 4.76 hectares of land covered by invasive plant species. A total of 3190 parcels were identified as falling within riparian zones, indicating systemic violations of land-use regulations and the need to update urban planning and land management documentation. The practical value of the developed GIS lies in its provision of a spatially coordinated basis for management decisions regarding renaturalisation, riverbed cleaning, restoration of coastal riparian zones, and the integration of water bodies into the city's green and blue infrastructure system. The geoinformation application on the ArcGIS Online platform contains an interactive web map, which includes the following thematic maps (Fig. 4):

- "Watercourse regularity" – demonstrates the degree of consistency of small river flows;
- "Seasonal rivers" – shows the risk of vulnerability to droughts and the catchment basins of small rivers;
- "Physical accessibility of river coastlines" – characterises the accessibility of the riparian zone for movement, the presence of barriers, shrubs, or buildings;
- "Protection of small rivers" – reflects areas with nature conservation status, coastal protection strips, and self-occupied territories;
- "Pollution of small rivers" – reflects the locations of garbage, discharges, silting, or local sources of pollution identified during field surveys;
- "River openness" – demonstrates the degree of accessibility of rivers to the community.

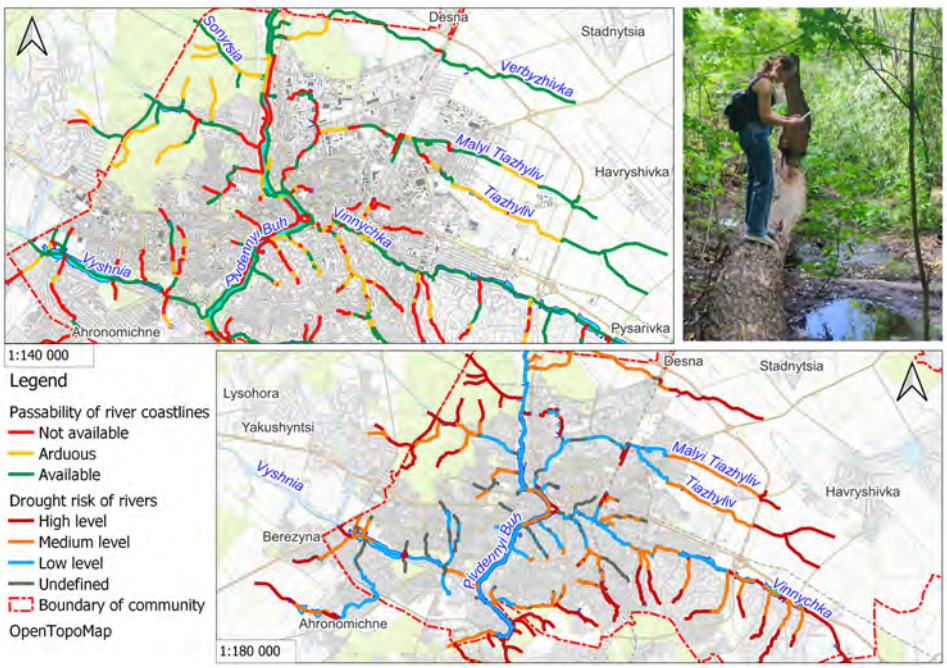

Fig. 4: Thematic maps of drought risks of small rivers and physical passability along the coasts of these rivers (Performed by the authors)

Additionally, an essential component of the project is the preservation of river ecosystem biodiversity; therefore, the "Protection of small rivers" map displays volunteer data and integrates datasets from the iNaturalist platform (Fig. 5). The practical value of the developed GIS lies in its provision of a spatially coordinated basis for management decisions regarding renaturalisation, riverbed cleaning, restoration of coastal riparian zones, and the integration of water bodies into the city's green and blue infrastructure system.

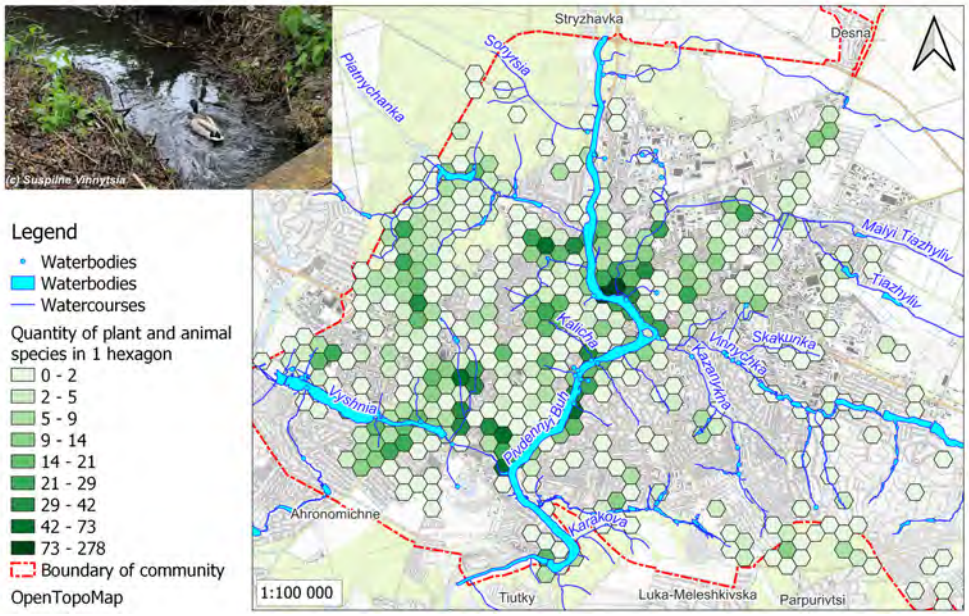

Fig. 5: Thematic maps of drought risks of small rivers and physical passability along the coasts of these rivers (Performed by the authors)

4 Discussion

The novelty of this study lies in the pioneering use of citizen science (namely, volunteer assistance) to refine existing GIS data on small rivers (less than 5 km in length) in Ukraine, using the example of Vinnytsia. This approach helped to identify previously undocumented historical names, drying segments, and barriers on the banks, thereby filling the gap between official data and real ecological conditions.

The institutional aspect. The project "Mapping Small Rivers in the Vinnytsia Community" was implemented as part of the Concept for the Development of Small Rivers in Vinnytsia until 2035. Ukraine also has a Water Code and Directive 2000/60/EC of the European Parliament and of the Council of October 23, 2000, establishing a framework for Community action in the field of water policy. Similar research projects in other countries must be conducted in accordance with their current legislation.

The information aspect. Obviously, the higher the quality of the initial data and materials, the fewer resources will be required for processing and standardisation. However, in regions with limited up-to-date data, additional capabilities and resources must be brought in.

The organisational aspect. Involving active pupils, students, residents, and other interested parties not only facilitates rapid data collection but also provides an opportunity to raise environmental awareness among citizens and expand the stakeholder base interested in addressing these and other ecological problems in the study area.

The technical aspect. Simple, accessible software tools for data collection should be used to implement such projects, as user levels will range from beginners to advanced geoinformatics specialists or urban planners. Most importantly, this project should not be a one-off but a systematic, well-supported initiative, either officially, through a specific institution/organisation, or through volunteers. Accordingly, it is necessary to determine who will be the administrator and owner of the geoinformation system.

5 Conclusion and Outlook

This research project was implemented for the first time in the Vinnytsia municipality to map small rivers, involving citizens, volunteers, and students. As a result of this project, more rivers than planned were identified and surveyed, and the data obtained is already being used in the restoration of the Skelna River and in the organisation of eco-initiatives on the Tyazhyliv River. The historical names of 34 small rivers that had been lost were also officially restored. Further research should focus on:

- assessing the potential for renaturalisation – identifying areas where riverbed restoration is possible most simply and effectively, and areas where the return of riparian zones is critically necessary;
- analysing the vulnerability to drought and climate change for different types of watercourses (ephemeral, temporary, permanent);
- developing a monitoring system (GIS, satellite and UAV data, public participation);
- integrating the results into urban climate change adaptation programs and Vinnytsia's Green Course.

Thus, this project develops not only a geoinformation model of the river network but also a scientific basis for strategic planning to restore aquatic ecosystems, a key element of urban climate resilience.

Acknowledgements: This study was conducted as part of the project “Mapping the Small Rivers of Vinnytsia Community for Conservation and Sustainable Management”, implemented with the support of the European Union within its Eastern Partnership Civil Society Fellowship Programme. The findings presented in this paper extend beyond the project’s initial data publication by providing a scientific justification for the VGI-based methodology for assessing urban climate resilience. The authors would like to thank the anonymous reviewers for their suggestions, recommendations, and helpful remarks.

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Exploring Pathways to Real-Time Responsive Disaster-Resilient Green Space Planning: A Case Study of Jinshan, Shanghai

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Abstract: The chemical plants encircling urban areas predicament poses a critical safety challenge in China's rapid urbanization. Taking the industrial-residential adjacent area in Shanghai's Jinshan Petrochemical District as a representative case, this study employs risk simulation and multi-source data analysis to construct a modular disaster-resilient green space system. A dynamic context-aware system, based on multi-sensor network perception and intelligent decision-making, is also developed to enable real-time evacuation guidance during disasters. The research provides a practically feasible and theoretically valuable solution for governing the spatial dilemma of chemical plants encircling urban areas.

Keywords: Hazard simulation, disaster-resilient green space planning, real-time response, context-aware interactive design

1 Introduction

China's rapid urbanization has exacerbated the “chemical plants encircling urban areas” pattern – residential neighbourhoods adjacent to petrochemical complexes – posing critical challenges to urban safety governance. The Shanghai Jinshan Petrochemical District exemplifies this predicament. The synchronous expansion of urban built-up areas and industrial facilities, coupled with multiple small-scale safety incidents such as gas leaks in recent years, has seriously threatened the safety of local residents' lives and property. The study area is situated in the adjacent zone between industrial and residential districts within the Jinshan Petrochemical Zone, bounded by the Shenhai Expressway to the north, Longquangang River to the east, and the administrative boundary of Jinshan District to the west, covering an area of 80.91 km² (Figure 1). Regarding safety governance in this region, the *Overall Plan and Land Use Master Plan of Jinshan District, Shanghai (2017-2035)* proposes to “strengthen the ecological protection between Shanghai Petrochemical, Shanghai Chemical Industry Park and urban living areas,” while the *Shelter Plan of Jinshan District (2014-2040)* stipulates a combination of nearby and remote evacuation for special disasters. However, no shelters have been designated within a 5-kilometer radius of the petrochemical park (LI 2016), resulting in the absence of disaster prevention and evacuation planning when petrochemical disasters occur.

The primary risk sources in the study area include crude oil tank farms and liquefied petroleum gas (LPG) tank farms. This study employs the ALOHA software to conduct hazard simulations of these risk sources. This simulation approach has been widely applied in petrochemical disaster research, including tank leakage emergency management (ZHANG et al. 2022) and single-hazard simulations (YUE et al. 2025).

Frequent disasters in the study area expose the inadequacy of traditional comprehensive disaster prevention planning in addressing sudden petrochemical risks (SHI 2016). Resilient city development offers a pathway beyond conventional planning limitations. Despite definitional

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debates among domestic scholars (PICKETT et al. 2004), consensus exists on its core connotations (SHI 2016) – herein defined as a city's capacity to rapidly disperse risks and restore stability following petrochemical accidents. This study operationalizes resilience thinking in spatial planning by systematically transforming ecological protection green spaces into disaster-resilient green space systems for emergency evacuation.

Petrochemical disasters are characterized by instantaneity and dynamic evolution, making context-aware technology a viable approach for achieving real-time response and emergency evacuation. This concept was first proposed by SCHILIT et al. (1994), who emphasized that a context-aware system can detect and respond to changes in the target user's environment, thereby providing timely and accurate services. DEY and ABOWD (2001) expanded this framework, emphasizing the delivery of information matched to users' tasks, locations, times, and activities. Currently, context-aware technology has been maturely applied in the field of interaction design (LIU 2024) and can be extended to real-time disaster response applications.

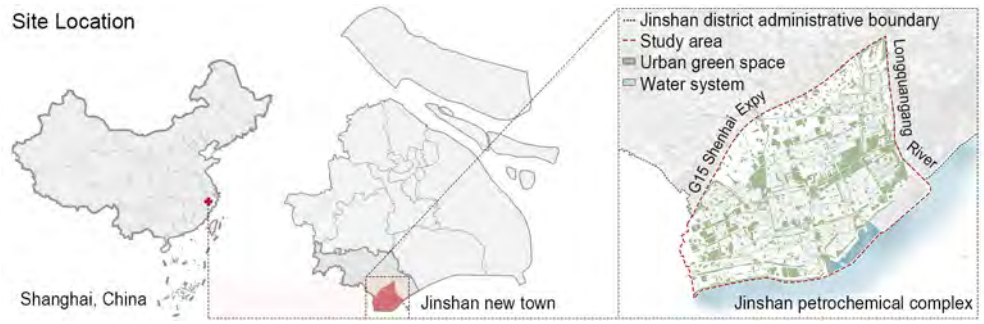

Fig. 1: Location and scope of the study area in Jinshan Petrochemical District, Shanghai

Based on the site's existing problems, upper-level planning, and current research status, this study proposes a spatial governance solution for the study area. First, multi-source data integration and risk simulation are conducted using GIS and ALOHA software to generate a risk classification map. On this basis, a modular disaster-resilient green space system is planned, and a dynamic context-aware system based on multi-sensor context perception is constructed. The evacuation interactive interface serves as the final presentation of the context-aware system, providing guidance for evacuation routes during disasters. This approach ultimately aims to fill the planning gap of shelters around the petrochemical park and enhance urban resilience in the region.

2 Modular Disaster-Resilient Green Space System

This study is based on risk simulation and multi-source data integration analysis. Field investigations and satellite image interpretation accurately identified key risk sources, including crude oil and LPG tank farms, and established a digital base map of the site. Disaster modeling was conducted using ALOHA software. Initial simulations targeted major petrochemical disaster types – namely vapor cloud explosions, toxic substance dispersion, and fire – for individual oil tanks (Figure 2). Subsequently, based on site-specific meteorological analysis, integrated simulations of explosions, toxic dispersion, and fire under different

thresholds were conducted using seasonal meteorological parameters (wind direction, wind speed, temperature) for both summer and winter. Toxic dispersion simulations employed a critical time threshold of 60 minutes. Simulation results from both seasons were overlaid to generate an explosion risk grade map (Figure 3).

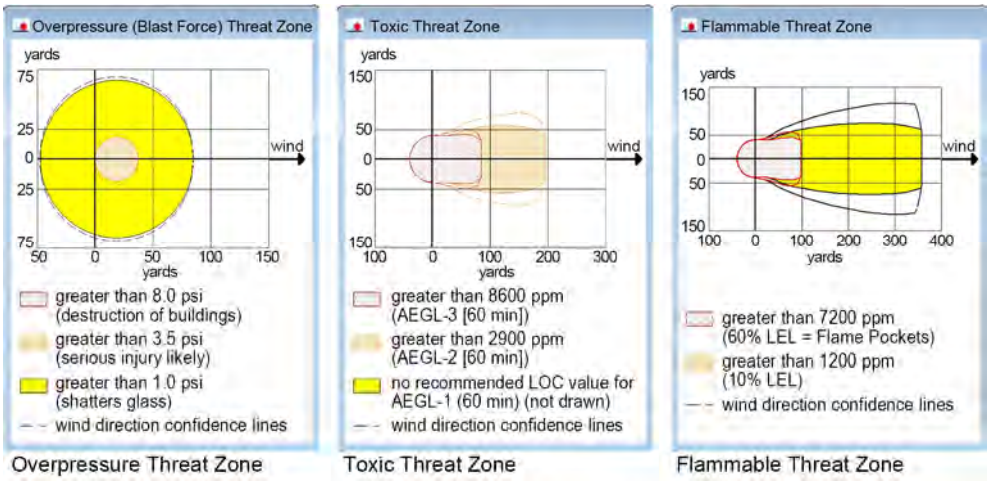

Fig. 2: Single hazard source simulation using ALOHA software

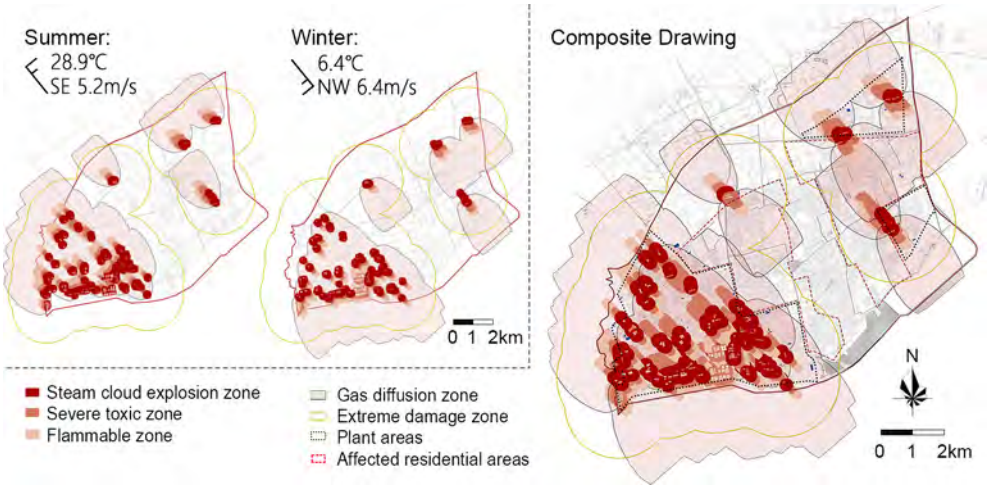

Fig. 3: Explosion risk level

Subsequently, multi-source data within the study area were acquired from open-source platforms and analyzed using GIS software for overlay analysis. Green spaces within the study area were classified by scale via GIS. The upper-level planning of the site's green space system (Figure 4-2) and the explosion risk grade map (Figure 4-1) were overlaid onto the existing green space classification map (Figure 4-3). Incorporating the site's transportation net-

work stations (Figure 4-4), GIS-based path selection was employed to determine evacuation and transfer routes for workers and residents around the explosion source within 10-minute and 60-minute timeframes following disaster occurrence (Figure 5). Based on these selected routes, the disaster-resilient green space system within the site was planned (Figure 6). The integration of this disaster-resilient green space system with the evacuation routes yielded the comprehensive disaster prevention and refuge plan for the site (Figure 7).

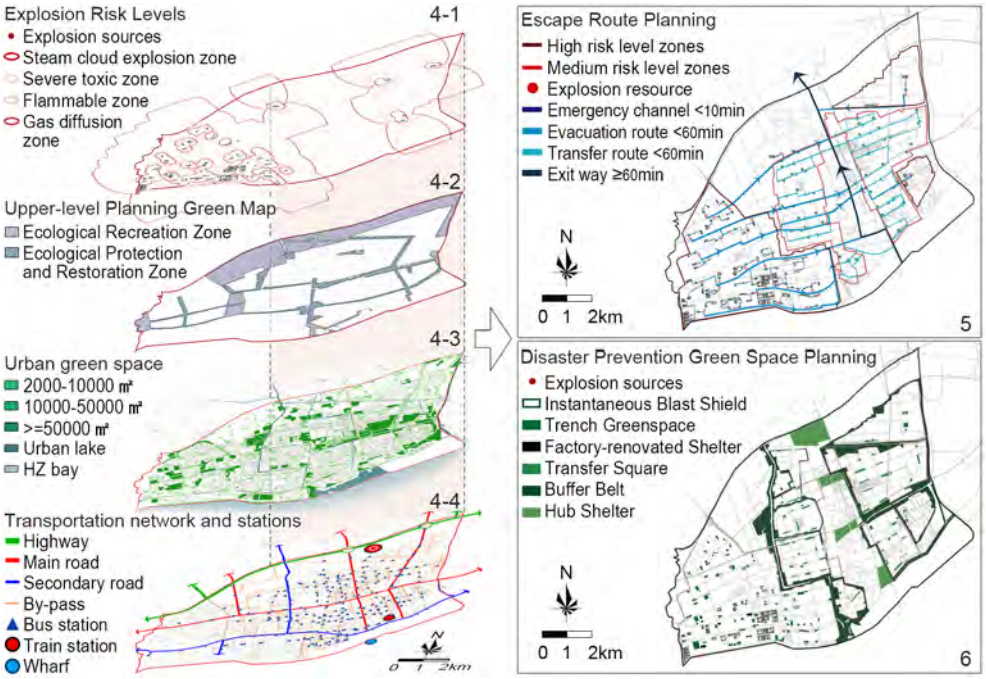

Fig. 4: Multi-source data overlay analysis for disaster-resilient planning

Fig. 5: Escape routes within 10 and 60 minutes of disaster occurrence

Fig. 6: Disaster prevention green space planning

The disaster prevention and refuge green space planning comprises two categories – isolation green spaces (Ix) and disaster-resilient green spaces (Rx) – which are further divided into six disaster prevention and refuge modules (Figure 7):

Ia. Instantaneous Blast Shield: The isolation layer itself consists of plants with excellent fire-resistant properties. Upon disaster occurrence, sensors detect intense noise or smoke, triggering fire-retardant water curtains and toxic gas-resistant sprays, thereby securing the first escape opportunity for workers within the industrial zone.

Ib. Buffer Belt: Including large-scale patch green space at the junction of industrial and residential areas, as well as linear green space within the residential area.

Ra. Trench Greenery: Planned along the shortest path principle from hazard sources to refuge facilities. Fire-retardant water curtains and toxic gas-resistant sprays on both sides of the trench are activated upon receiving disaster alerts.

Rb. Factory-renovated Shelter: Converted from abandoned factory buildings, serving as disaster-time waiting areas and temporary medical aid stations.

Rc. Transfer Square: Integrated with bus stops and street-side green spaces, designated for temporary vehicle parking during disasters.

Rd. Hub Haven: Receives evacuees during disasters; facilitates rapid mass transfer of affected populations out of the urban area during large-scale disasters.

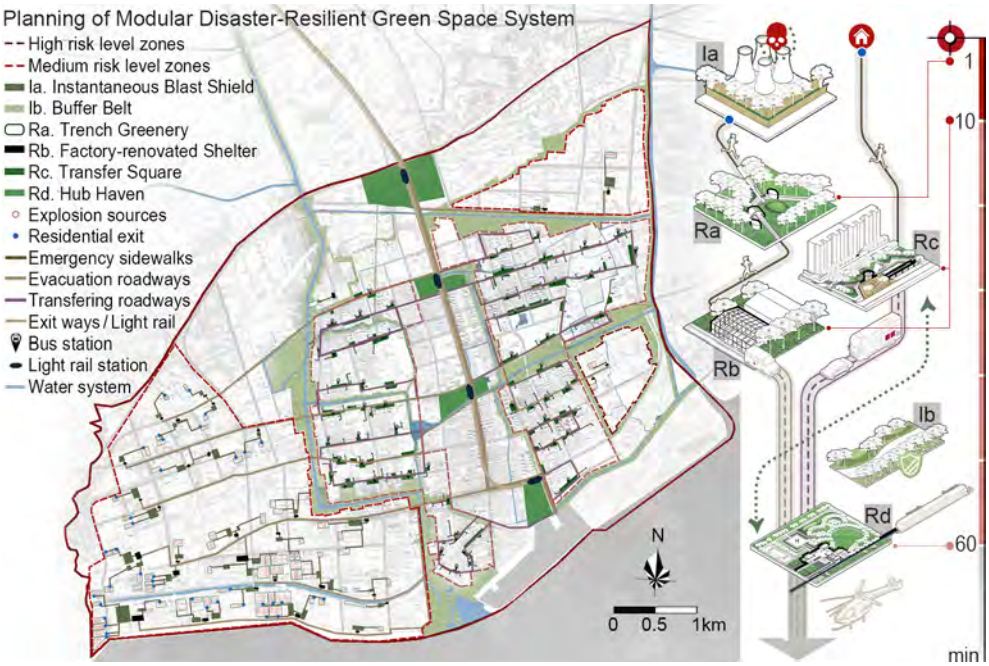

Fig. 7: Planning of Modular Disaster-Resilient Green Space System

The comprehensive disaster prevention and refuge plan for the site comprises three subsystems: the escaping system, the isolation system, and the refuge system. The escaping system primarily relies on the urban transportation network, providing clear directional guidance for evacuation through road design and signage systems. The isolation system consists of isolation green spaces, with Module **Ia**. forming an instantaneous multi-layered protective barrier that mitigates the initial disaster impact; together, Modules **Ia**. and **Ib**. prevent the continuous dispersion of toxic gases. The refuge system comprises disaster-resilient green spaces, serving as nodes for disaster-time rescue, temporary waiting, and safe transfer for residents and workers. By ensuring coordinated evacuation, hazard isolation, and emergency refuge, these three subsystems collectively enhance urban resilience in the area.

3 Dynamic Context-Aware Design

Escape flow design based on the escaping system effectively connects the isolation system and refuge system, enabling integrated utilization of the six green space modules. In accordance with disaster evacuation requirements, the evacuation timeline is divided into three critical phases – 1 minute, 10 minutes, and 60 minutes – forming the basis for a comprehensive time-phased evacuation procedure. This procedure accounts for the differentiated evacuation needs of two population groups – factory workers and urban residents – and integrates multiple transportation resources. For small-to-medium-scale disasters, buses, private cars, and shared bicycles facilitate rapid transfer of affected populations to large green spaces; for large-scale disasters, light rail and helicopters are deployed for mass evacuation (Figure 7).

The 0-10 minute period represents a critical window for personnel safety in the overall evacuation timeline. During this period, two population groups must act in parallel: factory workers urgently evacuate to Module **Rb**. (Factory-renovated Shelter) to await rescue, while surrounding residents rapidly transfer to Module **Rc**. (Transfer Square) for outbound evacuation. It is precisely at this critical stage that the context-aware system plays a crucial role. Sensors deployed across various modules monitor and collect environmental data at the moment of disaster impact, which is then uploaded to the cloud for processing. The system generates optimal evacuation route instructions and displays them intuitively on on-site interactive interfaces, guiding evacuees to quickly identify and follow safe evacuation pathways (Figure 8).

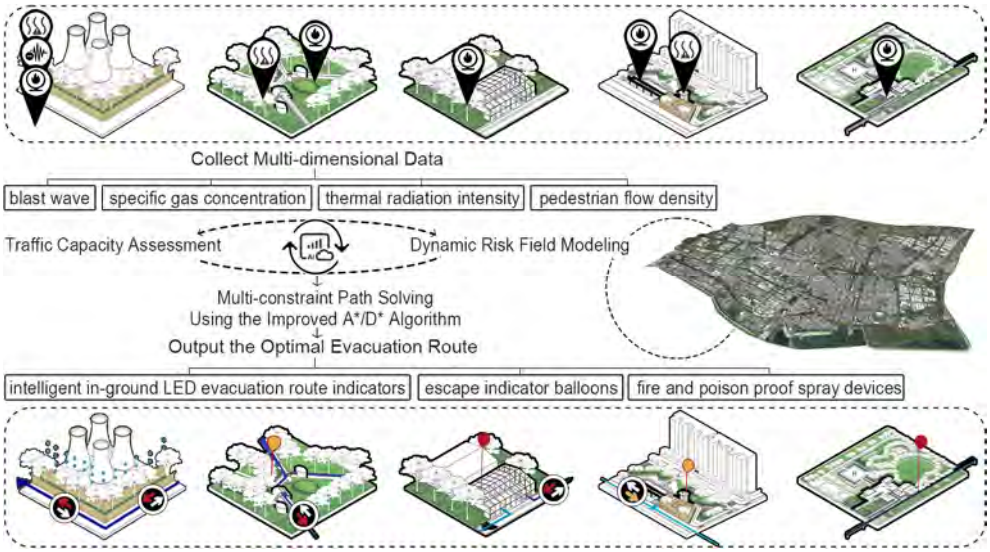

Fig. 8: Dynamic context-aware interactive design for the 0-10 minute evacuation window

The context-aware interactive interface consists of three components: intelligent in-ground LED evacuation route indicators, escape guidance balloons, fire and poison proof spray devices. To realize this interactive functionality, multiple types of sensors are first deployed at

critical disaster prevention modules to collect real-time multi-dimensional data, including blast wave, specific gas concentration, thermal radiation intensity, and pedestrian flow density. The poison proof spray devices are activated immediately when any monitored value exceeds the preset alarm threshold. Data collected through environmental and pedestrian flow monitoring are utilized for dynamic risk field modeling and traffic capacity assessment. The study employs an improved A*/D* algorithm combined with multi-constraint path solving to generate dynamically optimal evacuation routes that avoid congested or fire-threatened passages. Based on the intelligent decision-making results, in-ground LED indicators illuminate along the optimal path, while evacuation guidance balloons ascend above disaster-resilient green spaces and refuge facilities along the route, guiding workers and residents to evacuate safely and orderly.

During normal times, evacuation routes function as fitness trails, with regular community drills familiarizing residents with the system for rapid emergency evacuation. This dual-purpose design enhances spatial efficiency while strengthening risk perception and response capabilities through daily engagement.

4 Discussion

This study addresses the safety dilemma of “chemical plants encircling urban areas” as its core research issue, featuring clear practical orientation combined with operational feasibility and theoretical value. Methodologically, it integrates risk simulation (ALOHA), spatial analysis (GIS), and intelligent technology (context-aware systems), achieving innovative integration of technical approaches. In terms of outcomes, the proposed six disaster prevention and refuge modules (Ia/Ib/Ra/Rb/Rc/Rd) and three subsystem (escaping/isolation/refuge) designs are detailed and concrete, providing a reference operational framework for renewal and governance in similar regions. Overall, the study combines physical spatial planning with dynamic context-aware design, enhancing local populations' risk response capabilities and urban resilience.

However, the study has the following limitations:

1) Disaster simulations are based on specific meteorological parameters (summer/winter) and preset thresholds, whereas real disaster scenarios are often more complex and variable (e. g., multi-hazard coupling, secondary disasters), necessitating further validation of simulation result generalizability.
2) The proposed dynamic context-aware system framework currently remains at the conceptual design and simulation stage, lacking field deployment and operational testing; its system stability, response speed, and maintenance costs require empirical investigation.

Overall, the coordinated application of a modular disaster-resilient green space system (constructed through risk simulation and GIS-based path optimization), dynamic context-aware design (integrating sensor technologies), and community participation mechanisms offers the potential to achieve real-time, accurate evacuation route guidance during disasters, thereby enhancing urban resilience in areas where chemical plants encircle urban areas.

5 Conclusion and Outlook

This study addresses the complex spatial predicament of "chemical plants encircling urban areas" by transforming ecological protection green spaces into modular disaster-resilient spaces and introducing context-aware technology for dynamic response. Theoretically, it advances the intersection of resilient city and disaster-resilient green space planning; practically, it provides referential renewal and governance solutions for Jinshan and similar regions.

Despite limitations in hazard simulation and technological validation, the study's multi-method integration establishes a foundation for future research. Subsequent work may include pilot deployment, participatory App development, and digital twin technology (LI 2022) integration to facilitate practical implementation.

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Towards an Architecture of Shifting Boundaries: A Hydrodynamic Design Approach for Coastal Adaptation in Singapore

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Abstract: This paper reconceives the coastline as an adaptive interface co-produced by hydrodynamic forcing, sediment regimes, ecological succession, and governance decisions. Using Singapore's East Coast Line as a case study, it advances a computational design approach that treats hydrodynamic simulation as a generative instrument for spatial organisation rather than a post hoc verification step. The simulations are used in an exploratory, design-oriented mode to identify persistent hydrodynamic organisation and derive revisable spatial rules, rather than to predict long term morphodynamic evolution or future shoreline position. Transient flow simulations are interpreted as a pattern-reading practice: coherent, recurring structures in the velocity field are identified across seasonal tidal conditions and abstracted into a flow lattice that stabilises the relationship between environmental evidence and spatial decisions. A concise rule set then links lattice-scale indicators, including relative velocity reduction, wake persistence, turbulence concentration, and exchange corridor continuity, to modifiable design parameters such as orientation, spacing, porosity, and elevation of intervention elements. Nature-based strategies, including mangrove establishment, integrated multi-trophic aquaculture, and mineral accretion, are introduced not as decorative add-ons but as actuators through which hydrodynamic opportunities are converted into deposition, habitat formation, and controlled exchange that can be monitored over time. The results indicate that rhomboid arrays aligned with intersecting transport pathways can attenuate wakes while maintaining permeability, producing a porous field condition suited to incremental adjustment as environmental thresholds and governance priorities evolve. The contribution lies in formalising a transferable translation from hydrodynamic structure to design rule sets, and in framing coastal adaptation as an auditable and revisable process in which simulation, monitoring, and spatial reconfiguration remain explicitly coupled.

Keywords: Adaptive systems, coastal resilience, environmental simulation, nature-based design, computational fluid dynamics (CFD)

1 Introduction

Singapore's coastline is a critical test bed for adaptation to sea-level rise, storm tides, and land scarcity, conditions that increasingly require strategies beyond static hardening (NEWMAN & QIAO 2022). Conventional responses have favoured seawalls and groynes, which often transfer risk, disrupt coastal ecosystems, and generate adverse downstream effects that require continual reinforcement (BULLERI & CHAPMAN 2010, JUSTINE & SEENATH 2025). This research reframes the coastline as a negotiated threshold produced by water, sediment, organisms, and human decisions across time (Fig. 1). The central proposition is that environmental computation, used as a generative collaborator, can translate hydrodynamic patterns into spatial rules that foster ecological processes and human use without fixing the coastline in a single state (FRICKER & KOTNIK 2023); the approach builds on pattern-based design logics developed for dynamic landscapes (M'CLOSKEY & VANDERSYS 2017).

The contribution is twofold and uses the ongoing coastal development in Singapore's East Coast, with the Long Island Project as a case study area (URA 2025, NCCS 2025). First, it presents a method for converting site-specific hydrodynamic behaviour into a computational design set that guides the placement, orientation, and transformation of interventions. Second, it demonstrates how an interconnected computational workflow can mediate between scientific evidence and design speculation to produce coastal systems that evolve with changing conditions.

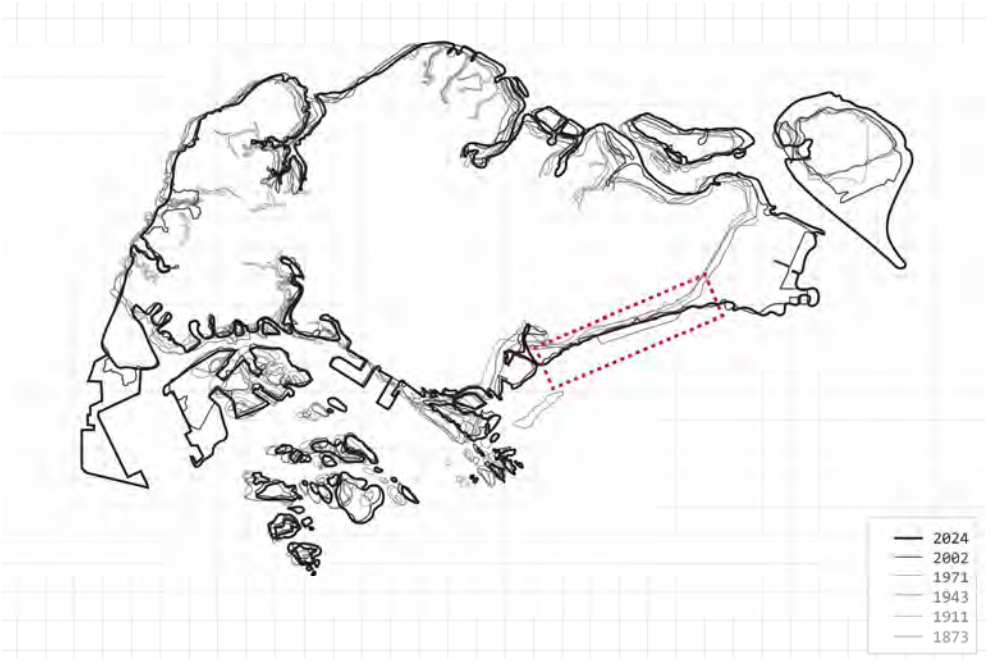

Fig. 1: Singapore's coastline evolution through the years. The red rectangle shows the area of interaction (image credits by the author).

The approach emphasises pattern literacy, understood here as the capacity to read and work with fluid patterns as drivers of form and programme, rather than as criteria for optimisation and rigid control. Existing pattern-based approaches in landscape architecture often transfer qualitative typologies into new contexts and iteratively adjust form against performance criteria. Morphodynamic approaches, by contrast, seek to represent coupled flow and sediment evolution so that landform change becomes a model output (SYVITSKI et al. 2010). The present research occupies a third position. It does not claim morphodynamic prediction at design time, and it does not treat simulation as an optimisation oracle. Instead, it advances hydrodynamic pattern persistence as a design evidence base, in which coherent flow structures that remain recognisable under plausible perturbations are treated as generative information from which spatial rules are derived.

This paper formalises a translation layer between hydrodynamic evidence and spatial organisation. A flow lattice is extracted from persistent current pathways and used as a scaffold for

design operations, while an explicit rule set links measurable indicators to modifiable parameters. Through this coupling, spatial decisions remain auditable and revisable: the same indicators that generate the design can subsequently be monitored and used to steer incremental change, rather than treating evaluation as a terminal stage after form is fixed.

2 State of the Art

Coastlines emerge from coupled hydrological, ecological, geological, and social processes, yet they are frequently managed as fixed boundaries through hard infrastructure that disrupts sediment regimes, fragments habitats, and transfers risk alongshore. In response, design research has increasingly turned toward process-based approaches attentive to feedback, uncertainty, and temporal change (CHAN & WAGSTAFFE 2023), while scholarship on cybernetics and environment has clarified how rule systems can mediate between dynamic processes and spatial organisation (ZHANG 2024). Against this backdrop, computational fluid dynamics has traditionally served coastal engineering as a tool for verification and risk assessment, but it is now being taken up as an exploratory medium within design. Ackerman et al. show how storm-event simulation can steer iterative development of protective dune configurations (ACKERMAN et al. 2020), while related work frames simulation as a recursive design practice structured by explicit decision logic rather than post hoc evaluation. Cantrell's Synthetic Ecologies articulates this position as a feedback-driven design framework for complex coastal environments (CANTRELL & HOLZMAN 2014, FRICKER 2022a). Wright's Siltcatcher similarly demonstrates how hydrodynamic organisation and sediment trajectories can be translated into spatial propositions with implications for wetland formation and shoreline change (WRIGHT 2020), and applied initiatives such as the Los Angeles River Integrated Design Lab emphasise workflows that connect modelling, scenario development, and stakeholder requirements within hydraulically constrained contexts (oOR 2022).

Together, these precedents signal a shift from simulation as a terminal check toward simulation as a source of design evidence. However, the translation from hydrodynamic output to spatial organisation often remains embedded in project-specific judgement, limiting its generalisability and making it difficult to audit, compare, or revise across scenarios. This limitation becomes particularly consequential in early-stage coastal adaptation, where multiple futures must be explored under uncertainty and where spatial decisions must remain adjustable as monitoring data and boundary conditions evolve. The framework developed here responds by formalising how persistent hydrodynamic organisation can be abstracted into a spatial scaffold and operationalised through an explicit rule set, enabling coastal configurations to be iteratively steered through declared indicators rather than fixed as a final-state solution.

3 Methods

The method is implemented as a coupled workflow in which transient hydrodynamic simulation is interpreted through an explicit translation procedure and tested for robustness under perturbed boundary conditions, after which four staged design operations convert analysis into spatial propositions (Fig. 2). The workflow is intended for early-stage decision-making, where the objective is to derive interpretable and revisable spatial rules from persistent flow organisation rather than to identify a single optimal configuration or forecast long-term morphological change.

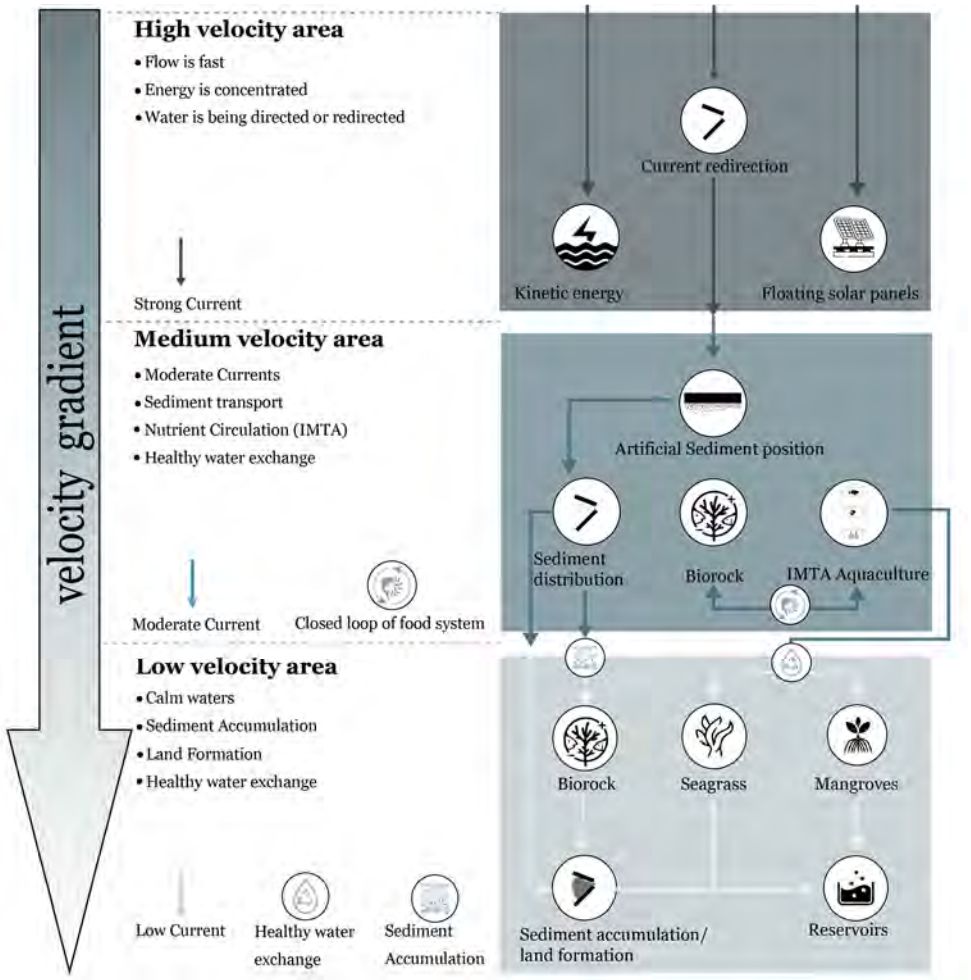

Fig. 2: Velocity regime-based response framework for the Singapore case study. The diagram links high, medium, and low current zones to corresponding process conditions and intervention families, including flow redirection, sediment management, ecological establishment, aquaculture, and reservoir formation, with arrows indicating directional dependencies and feedback. It functions as a conceptual rule map for subsequent design translation and scenario development (image credits by the author).

3.1 Computational Workflow and Verification

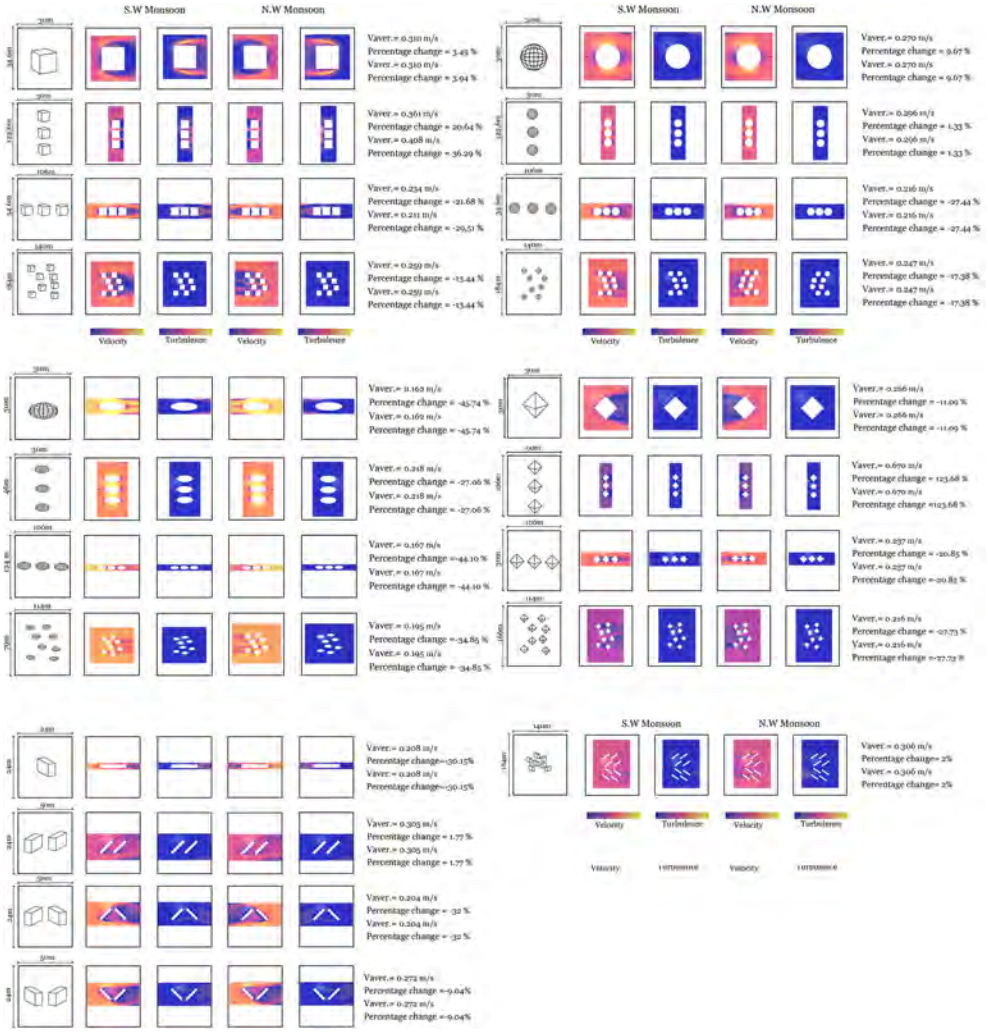

Fig. 3: Comparative CFD simulations of basic geometric prototypes and array configurations under South West and North West monsoon conditions. Each row presents the tested geometry and spacing, followed by velocity and turbulence fields for both flow directions and summary values of average velocity change. The matrix is used to identify recurring hydrodynamic effects of form and arrangement for design translation, rather than to predict long term coastal morphodynamics (image credits by the author).

Hydrodynamic analysis is conducted using a transient finite-volume Reynolds-averaged Navier – Stokes solver with k–ω SST turbulence closure, appropriate for shallow separated flows and wake dynamics relevant to nearshore interventions (DÍAZ-CARRASCO et al. 2021). Spring and neap conditions are represented through measured inflow velocities or tidal ele-

vations, with open boundaries implemented through zero-gradient outflow. Seabed roughness and near-wall treatment are calibrated within published ranges for comparable sandy substrates. Numerical soundness is assessed through mesh and time-step independence testing in zones where wake formation and corridor continuity govern spatial interpretation, maintaining Courant targets below unity. Verification focuses on reproducing canonical wake behaviour behind simplified obstacles at comparable Reynolds regimes and on confirming that velocity reduction and wake extent align with site-observed tendencies during ebb and flood.

To establish interpretable relationships between geometry and wake organisation, an exploratory series of simulations was conducted using elementary obstacle forms (cubes, spheres, ellipsoids, and rectilinear variants) within an idealised 30 m × 30 m computational domain representative of the nearshore scale of East Coast Park. The inlet velocity was set to 0.30 m/s, consistent with reported nearshore current magnitudes for the study area (MARTENS 2013). To reduce compounding uncertainty at this exploratory stage and to minimise numerical instability during comparative testing, the seabed was represented as flat and detailed bathymetry was omitted. Geometry processing and rule-based spatial translation were implemented as a parametric workflow in Rhinoceros 3D and Grasshopper (ROBERT MCNEEL & ASSOCIATES 2026A, 2026B). The model is used to resolve design-relevant hydrodynamic organisation rather than to deliver morphodynamic prediction (Fig. 3).

3.2 Rule Set for Design Translation

Spatial decisions are derived through a concise rule set that links recurrent flow features to modifiable design parameters. Rules are evaluated on a flow lattice, with each cell storing indicators extracted from transient simulation output, including relative velocity reduction, wake persistence, turbulence concentration associated with separation and shear layers, and the continuity of exchange corridors. These indicators are translated into parameters that remain legible within coastal landscape design: orientation relative to principal transport pathways, spacing to regulate wake interaction and system permeability, porosity to balance shelter and exchange, and local elevation adjustments to support sediment trapping and establishment within low-energy zones.

The set is applied through recurrent decision types observed in the simulations. Cells forming part of persistent exchange corridors are constrained to remain permeable and to avoid continuous barriers. Sheltered cells with stable velocity reduction and limited turbulence concentration are tuned toward porosity and micro-scale form that stabilise low-energy conditions while preserving exchange. Where turbulence concentrates and wake interference becomes unstable, spacing is increased and orientation is adjusted toward the principal streamline direction. Where retention increases and near-bed agitation remains comparatively low, crest height is minimally raised to support sediment trapping and early-stage colonisation without producing a hard edge that redirects flow around the system. Declaring these decision logics makes the translation from simulation output to spatial proposition traceable and revisable.

3.3 Flow Lattice Extraction, Robustness, and Sensitivity

Coherent organisation in the velocity field is interpreted to identify persistent current pathways, separation zones, and shear boundaries (Fig. 4).

A rhomboid lattice is fitted to dominant intersecting pathways and used as a scaffold for multi-scalar placement and tuning. Robustness is assessed through scenario perturbation rather than single-condition interpretation: inflow magnitude, direction, and water level are varied within realistic ranges, and outputs are read as indicator envelopes at lattice-cell scale. Pattern persistence is defined by the recognisability of dominant pathways and wake structures across scenarios, while sensitivity is assessed by identifying which indicators fluctuate most strongly and most frequently trigger parameter adjustments. In this case study, corridor continuity and dominant pathways remain comparatively stable, whereas turbulence concentration and wake interference show higher sensitivity near element edges and in zones of directional shear. These observations guide conservative rule activation in sensitive regions and permit local tuning where patterns remain persistent.

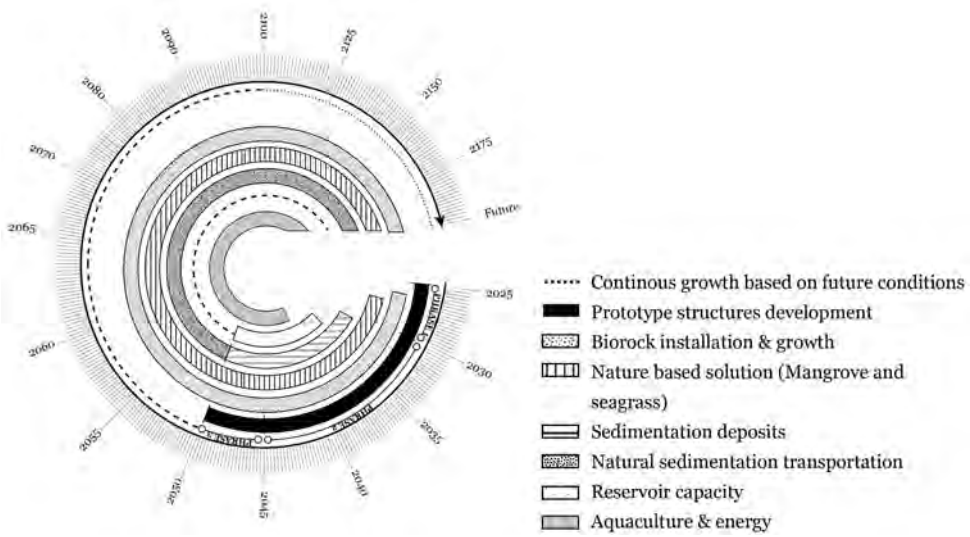

Fig. 4: Feedback loop diagram of the proposed system (image credits by the author)

The workflow is implemented through four design stages. Stage one establishes site intelligence and baseline conditions through historical mapping, remote sensing, and geographic information systems, supported by bathymetry, topography, tidal forcing, and prevailing current data. Stage two uses transient simulation as a design instrument by testing elementary volumes under site-calibrated conditions to identify repeatable relationships between geometry, wake formation, and corridor continuity. Stage three abstracts these relationships into a lattice-guided morphogenesis, where recurring flow organisation informs placement, spacing, alignment, and parameter variation; the rhomboid configuration emerges as effective for distributing attenuation while maintaining permeability for exchange (Fig. 5). Stage four couples the spatial system with nature-based strategies, including mangrove establishment, integrated multi-trophic aquaculture, and mineral accretion, and develops seasonal to decadal scenarios through which incremental growth, consolidation, or retreat can be steered in relation to monitored indicators and governance constraints.

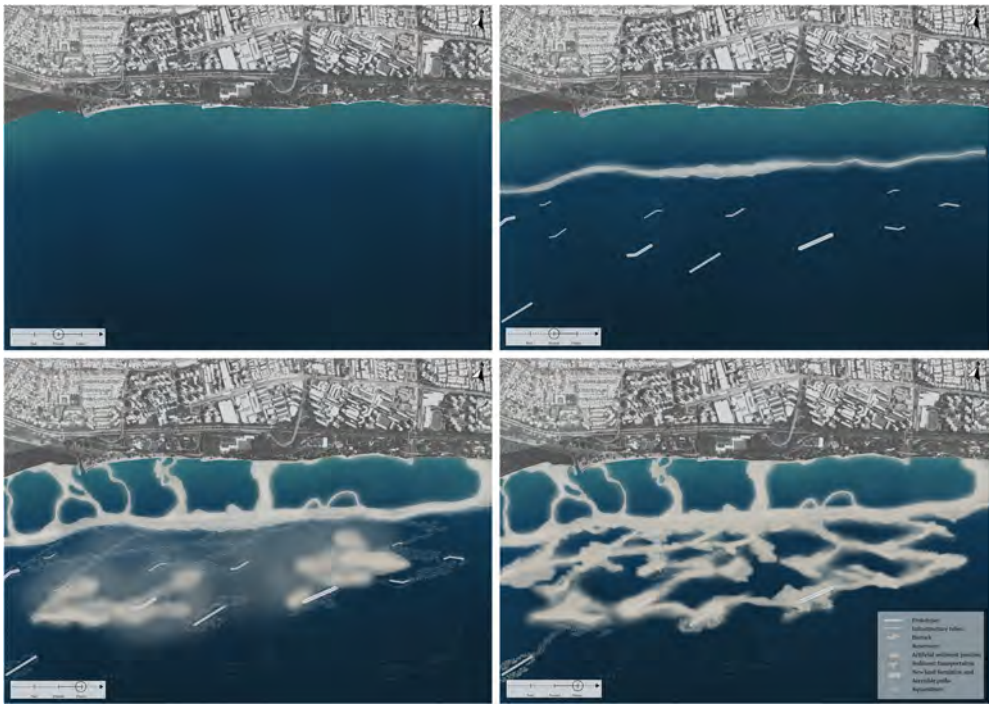

Fig. 5: Time sequenced dynamic masterplan for the Singapore case study, showing four scenario states generated through simulation informed, lattice guided rule translation. The sequence visualises how parametric placement and tuning of prototype elements are coupled with sediment management, ecological establishment, and productive coastal systems to form a porous and revisable coastal field. Layered annotations distinguish deployable components from process zones, supporting auditability, phased implementation, and indicator-based adaptation (image credits by the author).

4 Limitations and Validation

The method is designed to operate at the level of hydrodynamic structure rather than to deliver full morphodynamic prediction. Bed evolution, sediment supply constraints, and ecological growth dynamics are not modelled as coupled processes; deposition potential is therefore interpreted as an opportunity associated with sustained low-energy conditions rather than as a guaranteed volumetric outcome. Wave-urrent interaction is also treated in simplified form. In periods when wave forcing dominates, this can affect near-bed agitation and transport tendencies, particularly where wave orbital motion governs mobilisation. These constraints delimit the scope of inference: the workflow supports early-stage steering of spatial organisation through robust flow organisation, but it does not forecast long-term shoreline position or sediment budgets.

Validation is framed in terms of design-relevant reliability of flow patterns and of the translation procedure from simulation output to spatial decisions. Numerical soundness is supported through mesh and time-step independence testing in regions where wake formation governs interpretation, and through recovery of canonical wake behaviour consistent with the investigated regime (DÍAZ-CARRASCO et al. 2021). Simulation outputs are interpreted against literature-consistent expectations for sheltered zones, corridor continuity, and wake persistence. Robustness is further assessed through scenario perturbation: rule activation is restricted to locations where the associated flow organisation remains recognisable across plausible boundary variations, reducing the risk of overfitting to a single forcing state. In later project stages, the framework can be escalated toward coupled wave-current modelling and morphodynamic simulation at decision gates where higher predictive specificity is required.

5 Results and Discussion

Transient simulations consistently organised the nearshore flow field into intersecting pathways that remained recognisable across tidal scenarios. Aligning elementary volumes with these pathways produced repeatable wake regions characterised by reduced velocity and moderated turbulence, while maintaining through-flow necessary for exchange. When deployed as rhomboid arrays, the elements distributed attenuation without sealing the system, enabling sheltered cells to coexist with legible exchange corridors. These relationships were abstracted into a flow lattice that coordinates placement and morphogenesis across scales, allowing local tuning of orientation, spacing, porosity, and elevation without destabilising system-level connectivity.

To assess whether the rule set advances the design intent under uncertainty, three field-observable indicators were tracked across perturbed boundary conditions: velocity reduction within sheltered cells relative to baseline; residence time derived from transient pathline behaviour as a proxy for retention and settlement potential; and the persistence of exchange corridors linking sheltered zones to ambient flow. Because these indicators are directly coupled to modifiable parameters in the explicit set, they provide a basis for revising rule activation conditions as evidence accumulates, while keeping design claims open to independent scrutiny. Coupled with mangrove establishment, integrated multi-trophic aquaculture, and mineral accretion, the lattice supports feedbacks in which sheltered conditions facilitate substrate stabilisation and early colonisation, calibrated porosity sustains connectivity and trophic exchange, and distributed organisation limits single-point failure while enabling incremental adjustment in response to monitoring. This aligns with emerging evidence that co-interventions can enhance the performance and resilience of nature-based solutions across interacting stressors (FILZ et al. 2025). Although developed for Singapore's East Coast, the workflow is transferable to current-dominated deltas and estuaries with constrained sediment budgets, particularly where phased implementation and indicator-based monitoring are necessary to align spatial adaptation with adaptive governance.

6 Conclusion and Outlook

This study presents a hydrodynamic design approach that integrates site intelligence, transient simulation, and an explicit rule-based translation procedure within an auditable workflow.

By extracting a flow lattice from persistent hydrodynamic organisation and using it to steer rhomboid element families, the method translates flow structure into spatial configuration while preserving permeability and exchange. Declared indicators align simulation output with monitoring and enable scenario comparison without assuming fixed end states, supporting adaptive decision-making in early-stage coastal design (NEWMAN & QIAO 2022). Future work will incorporate higher-resolution morphodynamic coupling, improved representation of wave-current interactions, and field prototyping to refine rule activation conditions and strengthen links between simulated indicators and measured performance. More broadly, the framework supports a shift from fortification toward stewardship of evolving coastal interfaces, consistent with contemporary accounts of design's environmental turn (ZHANG 2024, FRICKER 2022b).

Acknowledgments

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Urban Watershed Vulnerability Index (UWVI): A Digital Framework for Nature-based Solutions and Socio-Ecological Design in Los Angeles

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Abstract: Urban regions face compounding challenges from climate change, environmental injustice, and aging infrastructure, requiring planning frameworks that align social and environmental vulnerabilities with ecological processes and future climate-related risk. This paper presents the Urban Watershed Vulnerability Index (UWVI), a forward-thinking geospatial framework that evaluates vulnerability using hydrologically defined sub-watersheds rather than political boundaries. Applied to 1,198 urban sub-watersheds in Los Angeles County, the UWVI integrates environmental, social, and climate-projection variables to reveal correlations and identify vulnerability hotspots. To bridge geospatial analysis and design, the UWVI overlays vulnerability scores with infrastructure datasets to identify strategic opportunities for implementing Nature-based Solutions and offers a replicable method for equitable, climate-resilient landscape planning.

Keywords: Urban watersheds, Nature-based Solutions, vulnerability index

1 Introduction

Digital technologies are reshaping how landscape architects map, model, and design urban landscapes. Cities are confronting interconnected challenges, including climate change, infrastructure strain, and persistent environmental injustice. Geospatial analytics offer opportunities to develop new data-driven strategies that address these challenges and support resilient, equitable, and multifunctional landscapes. Recognizing cities as living ecosystems and applying urban ecology principles in planning and design practices can simultaneously increase both environmental health and social well-being.

The Los Angeles Green New Deal (CITY OF LOS ANGELES 2019) is a comprehensive climate action plan that sets progressive goals to reduce emissions, expand urban forestry, manage stormwater, and ensure equitable access to green space. Achieving these benchmarks across the Los Angeles Region, spanning 10,400 square kilometers with nearly 10 million residents, requires data-driven methods that integrate natural processes with socio-environmental vulnerabilities. A framework is needed that moves beyond political boundaries toward ecologically significant units of analysis. Existing vulnerability indices, often organized by census tracts or city limits, fail to capture underlying ecological dynamics. To address this limitation, this study uses urban drainage basins, or sub-watersheds, as the primary unit of analysis.

This study introduces the Urban Watershed Vulnerability Index (UWVI), a composite index that integrates social, environmental, and climate-projection variables within hydrologically defined sub-watersheds. The UWVI evaluates 1,198 urban sub-watersheds across Los Angeles County and ranks them by relative vulnerability. Infrastructure data, including *storm drain networks, vacant lots, catch basins, and major roadways without tree canopy*, are evaluated

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in conjunction with the UWVI to identify opportunities to implement Nature-based Solutions (NbS) that address climate risks while providing social and environmental benefits.

NbS are especially well-suited for dense urban environments like Los Angeles, where a single intervention can support cooling, stormwater collection, habitat creation, pollution reduction, and social benefits simultaneously (COHEN-SHACHAM et al. 2016). A watershed-based framework reveals not only where vulnerability is concentrated but also where NbS can be strategically implemented to maximize socio-ecological performance.

1.1 Indices as Digital Planning Tools

Vulnerability indices combine various quantitative variables to measure and rank a population's exposure and sensitivity to a specific hazards (ATSDR 2024). These indices condense complex, multidimensional datasets into interpretable metrics that guide planning, policy, and design interventions. In California, indices such as CalEnviroScreen (OEHHA 2021) and the Healthy Places Index (PUBLIC HEALTH ALLIANCE OF SOUTHERN CALIFORNIA 2022) have played central roles in advancing environmental justice by identifying communities disproportionately burdened by pollution, socio-economic stressors, and health disparities. Additional indices, including the Tree Equity Score (AMERICAN FORESTS 2021) and the CDC Social Vulnerability Index (FLANAGAN et al. 2011) include urban tree canopy and disaster risks variables in their analysis.

Despite their value, most existing indices rely on political boundaries, particularly census tracts, which rarely align with ecological processes. Stormwater, flooding, nutrient flows, and pollutant transport operate within watersheds, not census tracts. As a result, indices based on political boundaries may misalign with ecological functions and limit the effectiveness of landscape interventions. The UWVI addresses this limitation by shifting the analytical scale to hydrologically defined sub-watersheds, creating an ecologically significant framework for design and planning. Additionally, unlike most existing indices, the UWVI incorporates climate projection data, allowing planners to anticipate future risks rather than relying solely on current or historical conditions.

The UWVI integrates fifteen variables across three indicators: Environmental *(% tree canopy, % impervious surface, % parks, heat severity, air pollution)*, Social *(distance to parks, % minority population, % poverty, asthma prevalence, population density)*, and Climate Projections *(temperature increase, increase in precipitation intensity, 50-year flood risk)*. Together, these variables provide a comprehensive and forward-looking assessment of socio-ecological vulnerability across Los Angeles County.

1.2 Performance and Co-Benefits of NbS

Nature-based Solutions (NbS) are strategies that use natural systems, ecological processes, or green infrastructure to address environmental, social, and climate-related challenges. They integrate vegetation, soils, and hydrological processes to provide measurable ecosystem services while enhancing human well-being and resilience (RAYMOND et al. 2017, COHEN-SHACHAM et al. 2016).

Urban trees are an example of the multifunctional potential of NbS. They intercept rainfall, reduce runoff, improve infiltration, and moderate urban heat through shading and evapotranspiration (HSU et al. 2021). Trees also improve air quality, enhance habitat connectivity, and

strengthen neighborhood identity. Other NbS interventions, such as bioswales, rain gardens, vegetated detention basins, permeable surfaces, and greenways, further improve water quality, pedestrian comfort, and microclimate while reducing flood risk.

NbS also offer substantial social benefits. Shaded streets and parks mitigate heat stress, green public spaces support physical and mental health, and community gardens or pocket parks strengthen social networks. NbS function across multiple spatial scales from individual parcels to neighborhoods and entire watersheds, making them versatile tools for both site-scale design and regional planning. Figure 1 visualizes NbS infrastructure opportunities and corresponding design strategies identified in the study.

While this study does not prescribe specific NbS treatments for each vulnerability indicator, it recognizes how different interventions mitigate multiple dimensions of vulnerability. Heat can be reduced through shade trees along major roads and expanded green space; flood risk can be addressed through trees, bioswales, rain gardens, and vegetated detention basins; and social vulnerabilities such as asthma prevalence or limited access to parks can be improved by increasing canopy cover, multimodal corridors, and converting vacant lots into community green spaces. These interwoven relationships highlight how NbS can simultaneously address many vulnerabilities even without one-to-one indicator matching.

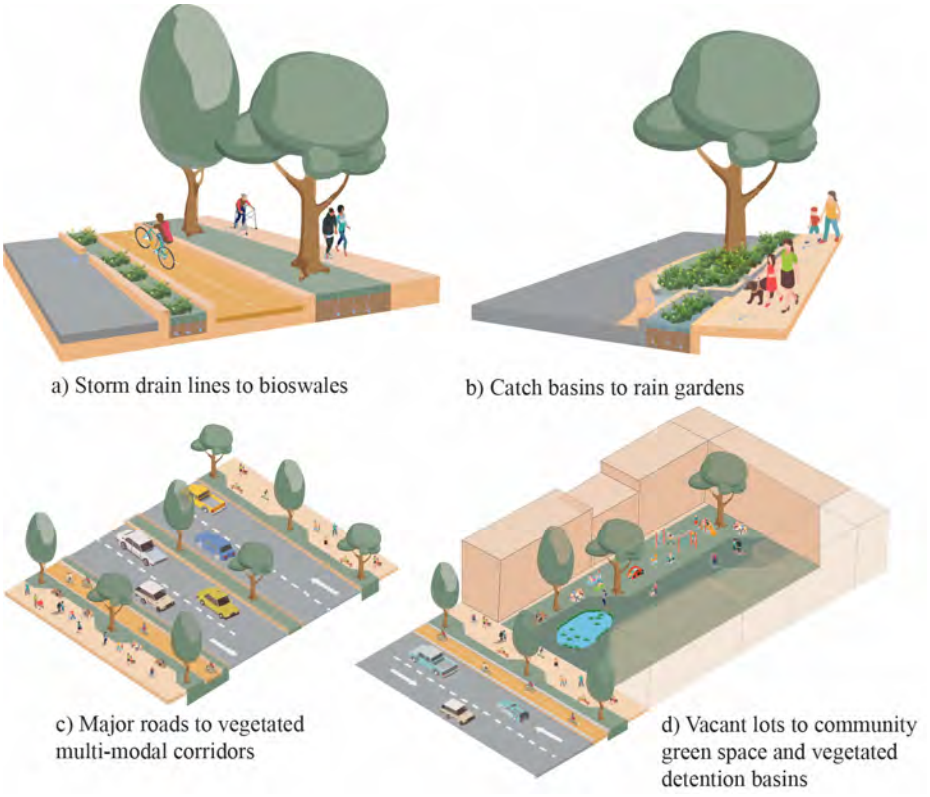

Fig. 1: Potential Nature-based Solutions interventions

1.3 The Significance of Watersheds

A watershed is the land area where precipitation drains to a common outlet, such as a river, coastline, or, in urban settings, stormwater infrastructure. Stormwater infrastructure distributes flows through networks of catch basins, detention structures, and storm drain lines, which manage runoff. Smaller sub-watersheds lie within greater watersheds, forming hierarchical hydrologic systems that organize how water, sediment, and pollutants move through urban landscapes.

Urban watersheds integrate both natural and engineered processes, making them essential for understanding runoff, infiltration, pollution transport, and flood dynamics. Because many NbS strategies directly influence watershed health by enhancing infiltration, slowing runoff, improving water quality, and moderating microclimates, watershed-scale planning supports more ecological functional designs that can also deliver social co-benefits**.**

1.4 Need for Equity and Resilience

Rapid urbanization and climate change are intensifying inequities across Los Angeles, with portions of the county being among the most densely populated and socio-ecologically vulnerable metropolitan regions in the United States. Low-income communities and communities of color disproportionately face environmental burdens, including limited tree canopy, reduced access to parks, high population density, elevated exposure to air pollution, and greater susceptibility to extreme heat and flooding. These conditions correlate with higher rates of respiratory illness, heat-related stress, and reduced overall well-being (EPA 2021).

Climate projections emphasize the urgency to address these inequities. Average temperatures in California may rise by up to 10°F by 2100, while extreme precipitation events may intensify by as much as 25% (BEDSWORTH et al. 2018). These impacts are unevenly distributed. Decades of redlining and systemic disinvestment have left marginalized neighborhoods with inadequate infrastructure, degraded air quality, and insufficient green space (HILLIER 2003). Today, more than one million Angelenos, disproportionately Black, Latino, and Asian, live within the 100-year floodplain (HOFFMAN et al. 2020).

NbS offer approaches to help redress these inequities. Integrating NbS within a watershed-scale vulnerability framework helps ensure that investments in urban greening and stormwater infrastructure reach the communities most in need.

2 Methods: The UWVI Framework

Los Angeles County contains 2,655 sub-watersheds delineated by the Watershed Management Modeling System (LACDPW 2020). Of these, 1,198 are classified as urban sub-watersheds, defined in this study as catchments located entirely within the urban footprint and containing demographic data (Fig. 2). Watersheds dominated by natural land or lacking residential populations were excluded so that the index reflects urban socio-environmental conditions.

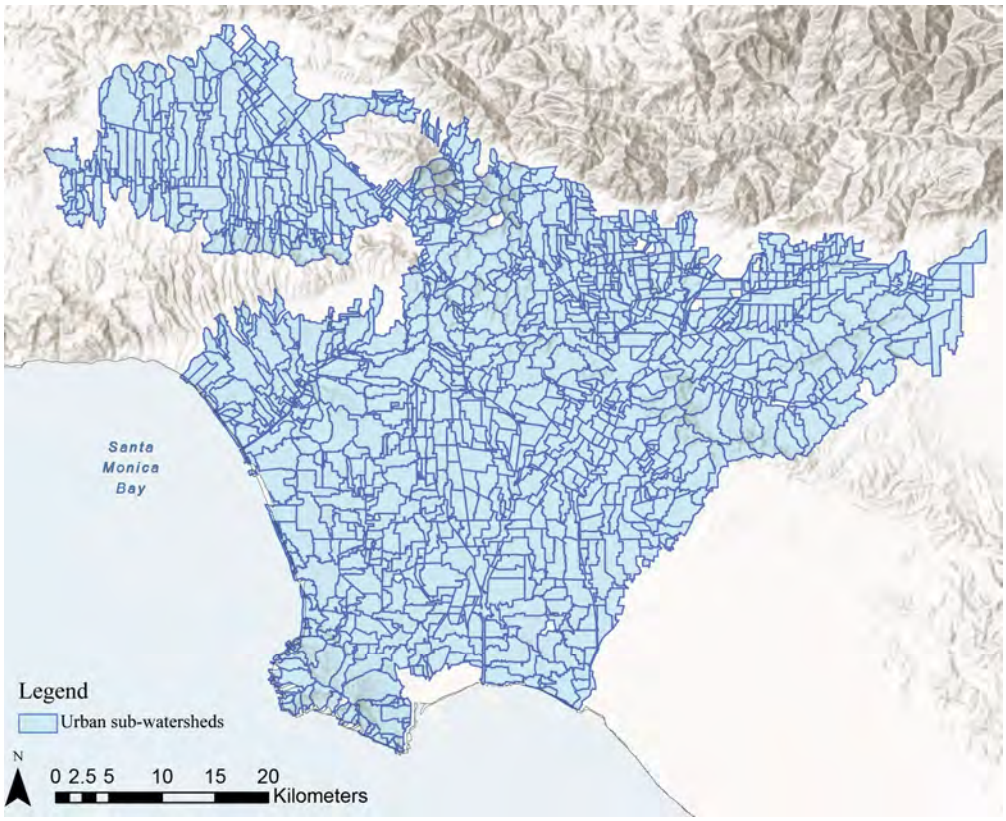

Fig. 2: Map of 1,198 urban sub-watersheds in Los Angeles County

2.1 Georeferenced Data and Spatial Resolution

Georeferenced UWVI variable datasets were obtained from multiple sources and organized in Environmental, Social, and Climate Projection indicators (Tab. 1). Environmental variables characterize existing landscape and urban conditions that influence exposure to heat, pollution, and ecosystem services specifically, *percent tree canopy, percent impervious surface, percent park, air pollution ($PM_{2.5}$), and heat severity*. Social variables characterize population demographics, health conditions, and socioeconomic factors that influence sensitivity and adaptive capacity. Social variables include the *percentage minority population, poverty, asthma prevalence, average distance to parks, and population density.* Population density is included as a social variable reflecting the concentration of people potentially exposed to environmental stressors and climate hazards, as higher density may intensify heat exposure, increase infrastructure demand, and heighten health risks in areas with limited green space. Climate projection variables project future stressors, including *projected increases in temperature, increased precipitation intensity, and flood risk (percentage of area within the 50-year flood plain).* Together, these indicators provide a comprehensive and forward-looking assessment of socio-ecological vulnerability across Los Angeles County.

The collected data varied widely in spatial resolution. Tree canopy, heat severity, and climate projections were provided as raster data, while demographic, land cover, and air pollution metrics were provided as vector polygons. Tree canopy data had the highest resolution at 1 meter, whereas climate projections were only available at a coarse 5-km resolution.

Infrastructure datasets that pose opportunities for Nature-based Solutions, including vacant parcels, storm drain lines, catch basins, and major roadways, were obtained from the Los Angeles County Planning Department GIS database. To determine roadway segments lacking canopy cover, the road network was clipped to a polygon version of the urban tree canopy dataset.

Table 1: Description of variables within each indicator

ENVIRONMENTAL (E)	**Description**	**Data Resolution**
% Tree canopy (%T)	The total amount of canopy within a city boundary, measured as the percentage of the land covered by branches and leaves	Raster: 1 meter
% Impervious (%I)	Percent of land that is impervious	Block
% Parks (%P)	Percent of land that is designated park space	Polygon
Heat Severity (HS)	Percentage of census tract that are hotter than the average temperature for the city as a whole.	Raster: 30 meter
Air Pollution (AP)	Annual mean particulate matter ($PM_{2.5}$) in air pollution	Census
SOCIAL (S)	**Description**	**Data Resolution**
Poverty (P)	Percent of population living below two times the federal poverty level	Census
Asthma (A)	Age-adjusted rate of emergency department visits for asthma	Census
% Minority (%M)	Percent of population that is not Non-Latino White	Census
Distance to Parks (DP)	Distance to nearest park. Average distance to all parks (over 5 acre)	Polygon
Population Density (PD)	People per square mile	Census
CLIMATE PROJECTIONS (C)	**Description**	**Data Resolution**
Temperature Rise (TR)	Increase of temperature by 2080	Raster: 5 km
Precipitation Increase (PI)	Increase in annual precipitation by 2080	Raster: 5 km
Flood Risk (FR)	Percent of land inundated by the 50-year storm	Raster: 30 meter

2.2 Geoprocessing in ArcGIS Pro

In ArcGIS Pro, all polygon-based variables were rasterized to a 30-meter pixel resolution to establish a common spatial resolution with each pixel holding a value. Using a 1-meter reso-

lution for countywide analysis would have been computationally unfeasible. A 30 × 30-meter cell (900 m²), which is less than ten percent of a typical Los Angeles city block, provides an appropriate scale for aggregating social and environmental data. Although the 5-km climate projections introduce uncertainty when downscaled to 30 meters, they still reflect regionally significant climate trends across the 10,400 km² study area.

Zonal statistics were then calculated for each indicator using sub-watersheds as analytical zones to produce an average raster pixel value for each watershed. A similar workflow was applied to the NbS infrastructure, with zonal statistics quantifying the number of catch basins and vacant parcels, and the lengths of storm drain lines and roadways lacking canopy within each sub-watershed. These attribute tables were exported to Excel for statistical analysis.

2.3 Statistical Analysis in Excel

UWVI indicator values were standardized using z-scores, normalized to a 0-1 scale, and grouped into the Environmental, Social, and Climate indicators. Indicator means were averaged to produce the composite UWVI score for each sub-watershed. In this study, the three indicators were equally weighted to avoid favouring any single vulnerability indicator. The framework is intentionally flexible, allowing alternative weighting schemes to be implemented through the Weighted Overlay tool in ArcGIS Pro based on planning priorities or available data.

2.4 Geospatial Attributes and Visualization in ArcGIS Pro

Statistical outputs from Excel were imported into ArcGIS Pro and joined to the sub-watershed attribute table, creating a single dataset that linked geospatial sub-watershed boundaries with both UWVI variables and NbS opportunities. UWVI scores were visualized using quartile percentile classifications to show gradients of vulnerability across the county. NbS datasets were visualized alongside these results, and a series of bivariate maps was generated to identify areas where high vulnerability spatially coincides with high potential for implementing NbS.

2.5 Workflow and Replicability for Other Cities

The UWVI workflow is designed to be replicable for other municipalities, regions, and watershed systems. Replication requires sub-watershed boundaries, urban infrastructure, environmental, and demographic datasets, as well as geospatial software like ArcGIS Pro or an open-source platform such as QGIS. While the specific variables chosen may vary, the core methodology includes rasterizing datasets, computing zonal statistics, standardizing variables, calculating composite scores, and overlaying infrastructure to provide a clear and flexible framework for combining vulnerability assessment with NbS planning.

3 Results

The UWVI shows notable spatial differences in social, environmental, and climate-related vulnerability across the 1,198 urban sub-watersheds of Los Angeles County (Fig. 3). Vulnerability hotspots appear in South Los Angeles, East Los Angeles, and parts of the San Fernando Valley. These areas share characteristics such as high imperviousness, high pollution

levels, low tree canopy, and social vulnerabilities, including high asthma rates, dense populations, poverty, and a high percentage of minorities. Many of these regions coincide with historically marginalized communities affected by redlining and systemic disinvestment.

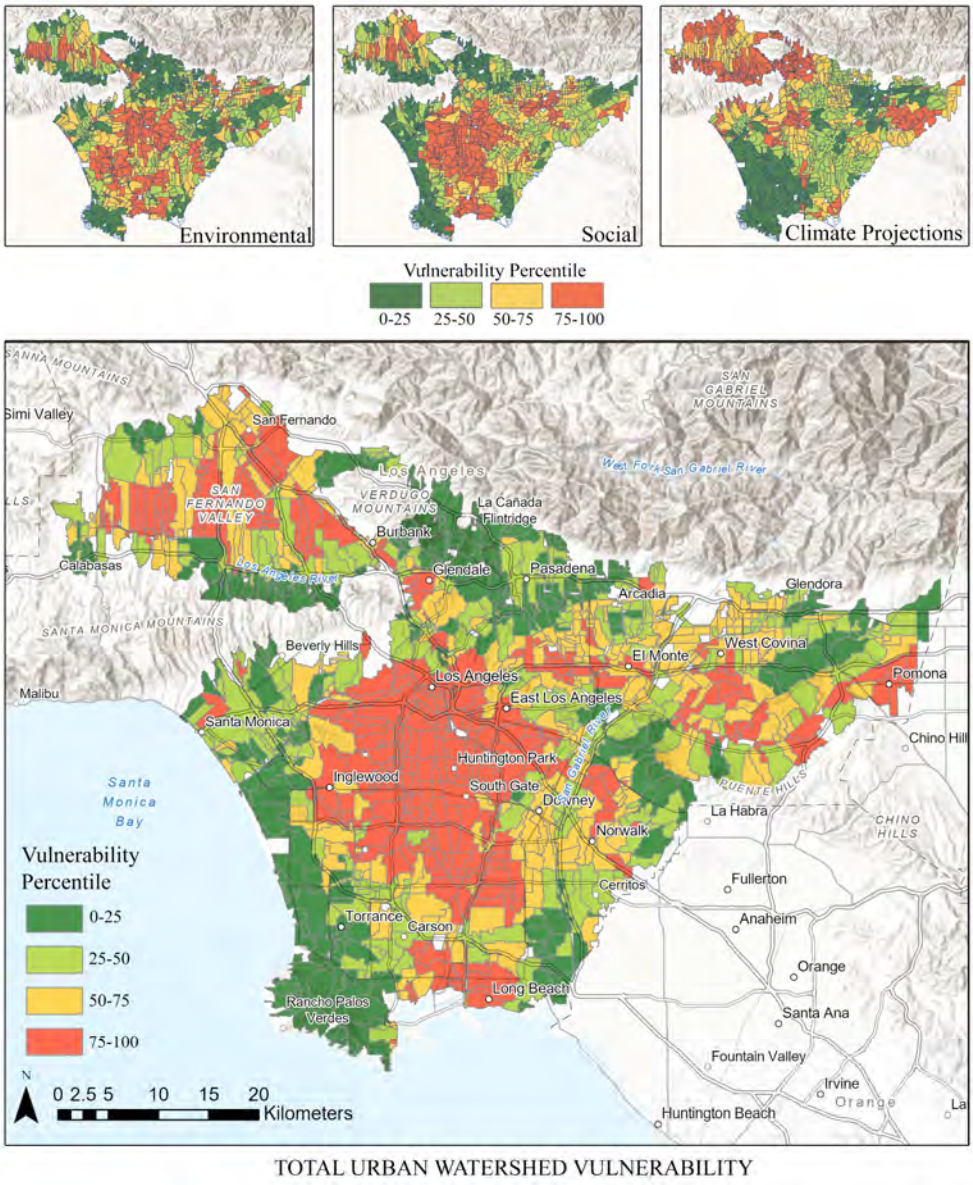

Fig. 3: The top three maps illustrate the watershed vulnerabilities for each of the Environmental, Social, and Climate Projection indicators. The bottom map presents the total Urban Watershed Vulnerability Index scores, a composite of all three indicators.

3.1 UWVI Correlation Analysis

A Pearson correlation analysis was conducted to examine the relationships among different vulnerability variables and indicators (Tab. 2). Correlation coefficients (r-scores) describe the strength and direction of relationships: values closer to 1 or -1 indicate stronger associations, with negative values indicating inverse relationships. The analysis revealed a strong correlation between social and environmental vulnerabilities, highlighting patterns of environmental injustice. Climate projection vulnerabilities showed no significant correlation with social or environmental vulnerabilities, suggesting that projected future climate risks are largely independent of existing socio-environmental conditions. However, this does not mean that climate change will impact all sub-watersheds equally. In fact, climate stressors are likely to intensify existing social and environmental vulnerabilities in already burdened watersheds. This underscores that social and environmental vulnerabilities should not be the only factors in urban planning and emphasizes the need to incorporate climate projections into resilience planning rather than relying solely on current conditions.

Table 2: Correlation matrix of Social and Environmental vulnerability variables (top) and overall Environmental, Social, and Climate Projection indicator scores (bottom), n=1,998 watersheds. Variable abbreviations correspond to those listed in Table 1.

	ENVIRONMENTAL					SOCIAL				
Variables	***%T***	***%I***	***%P***	***HS***	***PM***	***DP***	***%M***	***P***	***A***	***PD***
%T	1.00									
%I	-0.74	1.00								
%P	0.20	-0.42	1.00							
HS	-0.15	0.08	-0.18	1.00						
PM	-0.38	0.34	-0.08	0.03	1.00					
DP	0.00	0.03	-0.25	0.16	-0.03	1.00				
%M	-0.45	0.41	-0.16	0.05	0.32	0.02	1.00			
P	-0.53	0.55	-0.17	0.14	0.33	0.00	0.53	1.00		
A	-0.49	0.47	-0.16	0.15	0.34	0.04	0.50	0.61	1.00	
PD	-0.30	0.54	-0.25	0.05	0.15	-0.07	0.18	0.54	0.31	1.00

Indicators	***E***	***S***	***C***
ENVIRONMENTAL (E)	1.00		
SOCIAL (S)	0.62	1.00	
CLIMATE (C)	-0.17	-0.08	1.00

Correlation Coefficient (r)	**Positive**	**Negative**
< 0.20	Insignificant	Insignificant
0.20-0.40	Mild	Mild
0.40-0.60	Moderate	Moderate
0.60-0.80	Strong	Strong
0.80-1.00	Very Strong	Very Strong

3.2 Bivariate Mapping with NbS Infrastructure Opportunities

Opportunities where Nature-based Solutions could have the greatest impact were identified by overlaying the UWVI with infrastructure datasets using bivariate mapping (Fig. 4).

While the UWVI does not assess the feasibility of individual interventions, the overlay analysis reveals where high vulnerability aligns with physical conditions conducive to NbS implementation, offering a bridge between regional resilience planning and localized ecological design opportunities. Detailed, site-specific analysis at finer spatial scales would be required to determine the most appropriate NbS types and implementation strategies.

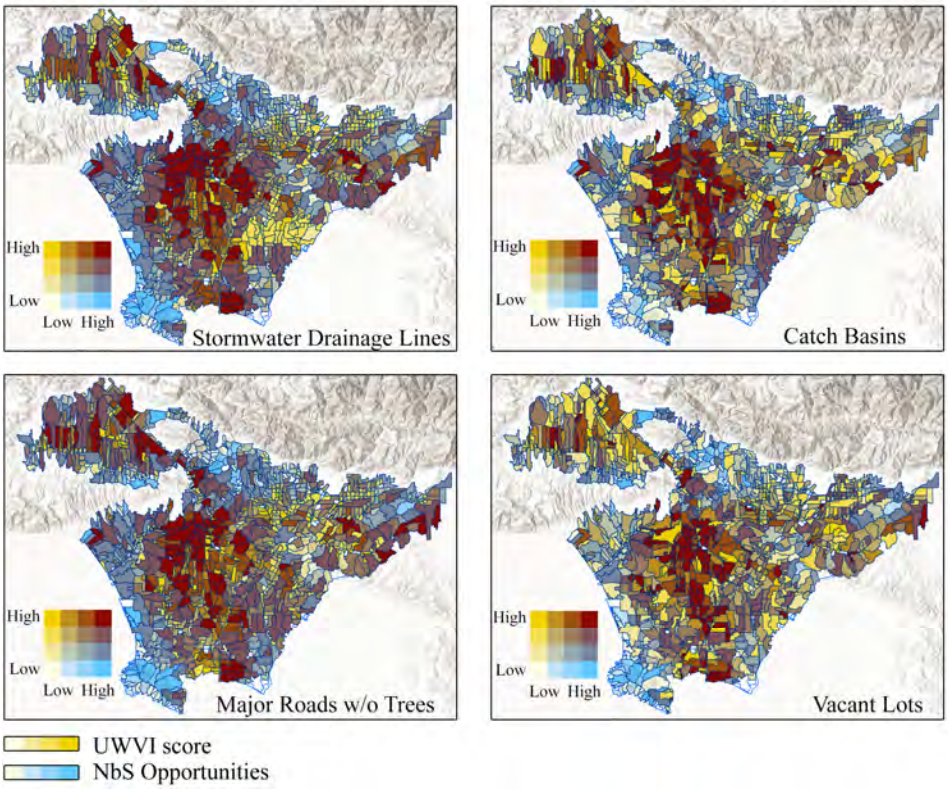

Fig. 4: Bivariate maps show the relationship between total Urban Watershed Vulnerability Index scores and opportunities for NbS

4 Discussion, Limitations, and Conclusions

The UWVI advances digital planning and design by integrating vulnerability indices, hydrology, and Nature-based Solutions into a unified decision-making framework. By organizing social, environmental, and climate-projection variables within hydrologically meaningful sub-watersheds rather than political boundaries, the index identifies where NbS can generate

the greatest socio-ecological benefit. This shift to an ecological unit of analysis supports planners and landscape architects in designing interventions that are both hydrologically functional and socially equitable. Incorporating climate projections allows the UWVI to address not only existing inequities but also emerging climate risks. In regions where extreme heat, intensified precipitation, and flooding are projected to increase, planning approaches that rely solely on present-day conditions risk underestimating future vulnerability. By integrating projected climate stressors alongside environmental and social variables, the UWVI supports forward-looking, resilience-oriented planning that anticipates how climate change may amplify existing disparities and reshape exposure patterns.

The integration of infrastructure datasets strengthens the connection between analysis and implementation. Spatial overlays of streets, parcels, and stormwater systems identify where NbS interventions are both feasible and needed. For example, streetscape greening can mitigate extreme heat and air pollution, and provide safe transportation corridors; vacant parcels can be repurposed as parks or vegetated detention basins; and stormwater infrastructure can be integrated with bioswales or rain gardens to reduce runoff and improve water quality. This multi-layered framework enables the UWVI to support interventions at multiple scales, from localized design strategies to watershed-level planning.

4.1 Limitations

While sub-watersheds represent an ecologically functional unit of analysis, they are larger than commonly used census tracts. Within the study area, 1,198 urban sub-watersheds contain approximately 1,990 census tracts, with an average sub-watershed size of 207 hectares compared to an average census tract size of 130 hectares. Although larger, sub-watersheds remain sufficiently granular at the regional scale to capture meaningful spatial variation while offering advantages for understanding and enhancing natural systems and ecological processes.

Aggregation of data at the sub-watershed scale may mask localized conditions within individual neighborhoods or parcels, particularly when social vulnerability varies within a single watershed, a limitation also present in census-tract-based analyses. Although the UWVI reduces spatial resolution by summarizing indicator values at the watershed level, this trade-off supports more effective Nature-based Solutions by aligning planning and design interventions with hydrologic processes, enhancing their long-term functional and ecological performance.

4.2 Conclusions

Overall, the UWVI demonstrates how multi-scalar, data-driven methods can guide equitable and ecologically grounded planning decisions. By integrating environmental, social, and climate projection variables within hydrologically meaningful units and linking vulnerability patterns to on-the-ground NbS opportunities, the UWVI offers a replicable framework for cities seeking to develop climate-resilient, multifunctional, and equitable landscapes. As urban regions confront intensifying climate pressures, approaches such as the UWVI can help ensure that investments in green infrastructure are targeted, effective, and aligned with both ecological processes and community needs.

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Improving Riparian Preservation and Restoration through a Low-Cost Cross-Scale Digital Workflow: A Case Study of the Selamat River Corridor, West Kalimantan, Indonesia

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Abstract: Tropical riparian corridors in data-poor river systems face intense land-use pressure that limits evidence-based planning. We develop a low-cost cross-scale digital workflow for the Selamat River corridor (West Kalimantan) integrating Sentinel-2 landscape context, UAV orthomosaic cover metrics, smartphone LiDAR-like scans, and vegetation plots. UAV results indicate a settlement-agro gradient (mean built cover 51.4% vs. vegetation cover 48.6%), while plot-based Shannon diversity (H′) adds ecological quality signals. Using explicit decision rules, we derive segment-level preservation/restoration priority outputs for segments with complete UAV panels, intended as auditable decision support for local agencies, village governments, and community groups.

Keywords: Riparian corridor, cross-scale workflow, UAV photogrammetry, Smartphone LiDAR, tropical river

1 Introduction

1.1 Riparian Corridors in Data-Poor Tropical River Systems

Riparian corridors are vital links connecting terrestrial and aquatic ecosystems. Vegetation structure and composition here support habitat functions, microclimate quality, bank stability, and sediment or nutrient filtration before runoff reaches water bodies. In tropical landscapes facing intensive land conversion, riparian corridors are often the first to respond to land use pressure and climate change, serving as the last line of defense for freshwater biodiversity and hydrological quality (LUKE et al. 2019, SOUTER et al. 2020).

In Southeast Asia, agricultural expansion has created highly fragmented land-use mosaics along tropical rivers. Studies show that riparian vegetation directly affects river ecosystem stability, from macroinvertebrate communities to semi-aquatic fauna, as well as flood and erosion buffering capacity (TAN et al. 2022, HARIANJA et al. 2024). However, these ecological benefits depend on the width, continuity, and structure of vegetation, not merely the existence of formal boundaries.

Simultaneously, tropical rivers are living spaces. Linear settlements, river-based mobility, and daily economic practices make riparian corridors active socio-ecological spaces rather than passive protected zones. Changes in riparian vegetation and hydrology directly alter

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risks, livelihood opportunities, and spatial access for riverbank communities. In inaccessible inland rivers, degradation often goes undocumented, hindering evidence-based preservation and restoration planning.

1.2 Digital Landscape Methods for Riparian Assessment

Remote sensing and digital landscape modeling allow for more systematic riparian assessment. Medium-resolution satellite imagery like Sentinel-2 is widely used to capture landscape context and vegetation dynamics via vegetation and water indices (NONES & GUERRERO 2019, ZHANG et al. 2025). At finer scales, UAVs and LiDAR reveal three-dimensional vegetation structure, including width, fragmentation, and vertical heterogeneity (GUO et al. 2021, CHEN et al. 2025).

Yet, most studies rely on a single scale. Satellite approaches offer broad coverage but lack structural detail, while studies focusing on 3D detail typically use expensive airborne LiDAR or UAVs inaccessible to many developing country institutions. This gap is particularly acute in data-poor tropical rivers, where the need for cross-scale information clashes with budget and technology constraints.

Recently, interest in low-cost 3D scanning, including smartphone-based LiDAR and lightweight photogrammetry, has grown. Comparative studies show that while less precise than professional systems, low-cost devices yield sufficient structural data for initial ecological analysis and site-based planning (ALIJANI et al. 2022, BALESTRA et al. 2024). However, integrating this technology with satellite and UAV data remains rarely explored in tropical riparian contexts. Conceptually, we frame riparian belts as cross-scale green infrastructure whose performance depends on corridor configuration within a broader land-use mosaic. Digital outputs (maps, cover metrics, and 3D views) are treated as boundary objects that help stakeholders negotiate feasible preservation and restoration actions.

1.3 Gap and Objectives: A Low-Cost Cross-Scale Workflow

This review identifies three main gaps. First, workflows explicitly integrating free satellite imagery, UAV products, low-cost 3D scanning, and field biodiversity data are limited. Second, smartphone LiDAR is almost untouched in riparian ecology literature despite its potential for hard-to-access rivers. Third, few studies position digital riparian outputs as tools for decision support and planning conversations rather than just technical diagnoses.

This study addresses these gaps using the Selamat River corridor in West Kalimantan, an inland tropical river facing land conversion and access constraints. We have two main objectives. First, to develop a low-cost cross-scale digital workflow linking satellite imagery, UAV orthomosaics, smartphone LiDAR, and field vegetation diversity indices to assess riparian condition. Second, to demonstrate how this workflow helps distinguish preservation and restoration zones to support transparent and negotiable planning decisions.

Methodologically, this article offers a workflow replicable in other data-poor tropical rivers. Practically, we show how affordable technology combinations provide relevant information for landscape architects and regional planners, ensuring the resulting maps and metrics serve as tools for socio-ecological deliberation rather than rigid zoning determiners.

2 Study Area

2.1 The Sungai Selamat Corridor

The Selamat River, a tributary of the Kapuas River system in West Kalimantan, Indonesia, flows through inland villages in North Pontianak before reaching the main Kapuas channel. Hydrologically, the corridor is influenced by rainfall regimes and Kapuas floodplain dynamics characterized by year-round water surplus (FIBRIANTIKA et al. 2021). Consequently, riparian vegetation changes and riverbank modifications interact directly with inundation fluctuations, bank erosion, and local water quality.

Geomorphologically, the corridor lies on a flat alluvial floodplain where riparian belts are productive but vulnerable to land-use change and narrowing. Native riparian vegetation is increasingly fragmented into gardens, fields, and linear settlements. The corridor is also a living space: linear settlements, mixed livelihoods, and river-dependent access mean that changes in riparian condition translate into everyday risk, access, and livelihood impacts (HIRAOKA 1985, DERBILE 2014).

2.2 Land Use and Riparian Context

Across the Kapuas watershed, land-use conversion to agriculture and settlement affects hydrology and water quality (FIBRIANTIKA et al. 2021, TANAKA et al. 2021). Along the Selamat River, the mosaic shifts from mixed gardens/secondary forest upstream to stronger plantation and settlement pressures mid-downstream, narrowing riparian belts.

Locally, field observations reveal distinct contrasts between relatively intact and degraded corridor segments. Segments with wider vegetation belts tend to have more stable banks and layered canopy structures. Conversely, segments narrowing to a few meters, especially those bordering rice fields, monocultures, or settlements, are more prone to bank erosion, local sedimentation, and vegetation simplification. This contrast is assessed in detail using satellite data, UAVs, smartphone-based 3D scanning, and vegetation plots in the Methods and Results sections.

2.3 Planning and Policy Background

The Selamat River corridor falls under Indonesia's spatial planning and river protection framework, where riparian buffer rules exist but are often weakly enforced through RTRW and detailed spatial plans. Empirical studies show persistent implementation gaps: buffer boundaries are frequently unclear in planning documents and supporting institutions are not consistently operational, leaving protective functions largely normative (NADHIRA & BASUNI 2021). In practice, riparian buffers are therefore often treated as reserve space for plantation and linear settlement expansion. For planning, it is important to distinguish between "legal maps" (RTRW buffers, setbacks, HCV zones) and "social maps" embedded in everyday use (gardens, inherited land, fishing spots, and access routes). The workflow developed here is positioned to help visualize these overlaps, so preservation and restoration priority outputs function as a starting point for deliberation rather than a final zoning verdict.

Table 1: Overview of data sources, derived products, and indicators used in the low-cost cross-scale workflow along the Selamat River riparian corridor

Data source	Product / output	Spatial unit (analysis unit)	Resolution / extent	Indicators (used in paper)	Notes
Sentinel-2 L2A	Composite imagery	Landscape corridor buffer	10–20 m	NDVI; optional water index	Landscape/floodplain context
UAV RGB (Autel Evo 2 Pro)	Orthomosaic	UAV segment + tiles/samples	~2.82 cm/pixel (GSD)	Cover metrics (veg/built/bare/water-shadow); simple fragmentation (patch/gap)	Core Results 4.1-4.2
UAV photogrammetry	DSM (visual proxy)	UAV segment	(visual)	Relative surface roughness / 3D proxy (not CHM)	No absolute canopy height
Smartphone LiDAR-like (Polycam)	3D mesh / point cloud	Representative patch	scan radius ±15–20 m	Relative height stats (max/mean/variance)	Local vertical structure
Vegetation plots	Plot dataset	Plot 25 × 25 m	plot-based	Shannon H′; richness; n individuals	Ecological quality signal
Rapid qualitative insights	Field notes / labels	Segment level	n/a	Social function; problem locations; conversion history	Social value/exposure

3 Data and Methods

3.1 Overall Low-Cost Cross-Scale Workflow

We develop a low-cost, cross-scale workflow linking Sentinel-2 landscape context, UAV orthomosaic cover metrics (with DSM as a relative structural proxy), smartphone LiDAR-like scans (Polycam), 25×25 m vegetation plots (H′), and rapid qualitative insights. Nested units (plots→patches→UAV segments→satellite context) are integrated via transparent decision rules to produce preservation/restoration priority outputs.

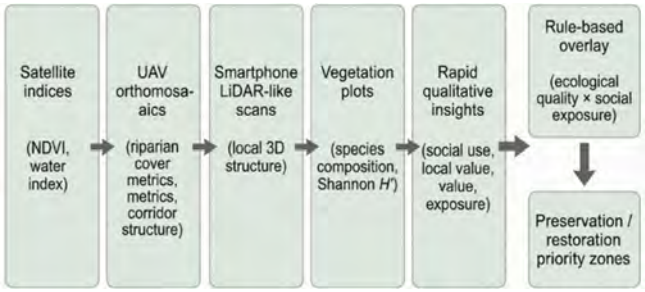


Fig. 1: Low-cost cross-scale workflow integrating Sentinel-2, UAV orthomosaics/DSM, smartphone LiDAR-like scans, vegetation plots (H′), and rapid qualitative insights into rule-based priority outputs

3.2 Complementarity of Cross-Scale Information

Each data source contributes a distinct layer across nested scales: Sentinel-2 provides landscape context, UAV orthomosaics quantify corridor-scale cover, Polycam supports local 3D interpretation, vegetation plots provide H′, and rapid insights add social context for interpreting priorities.

3.3 Satellite Imagery and Landscape-Scale Indicators

Satellite imagery was used to (i) provide landscape/floodplain context around the Selamat River corridor and (ii) derive watershed-scale vegetation indicators to contextualize UAV segments. We used Sentinel-2 Level-2A (10-20 m) from low-cloud periods and processed imagery in a cloud platform (e. g., Google Earth Engine) for replicability (Pu et al. 2021). To reduce single-date acquisition bias, we generated a multi-image composite within a comparable time window, then applied standard pre-processing (study-area cropping, cloud masking) and calculated NDVI as a proxy for greenness and vegetation vigor. Where relevant, a simple water/wetland index was computed optionally to reflect floodplain dynamics.

3.4 UAV Data for Corridor-Scale Vegetation Structure

UAV surveys captured corridor-scale structure across segments representing settlement-agro pressures, using an Autel Evo 2 Pro RGB camera (122 m flight altitude; ~2.82 cm/pixel GSD; 4 October 2025). Flight lines followed the river to capture both banks continuously.

Corridor-scale cover metrics are derived from complete UAV panels in Segments 1-2 (Segment 1: n=4 panels; Segment 2: n=8 panels); panels serve as corridor sampling windows and are not one-to-one equivalents of 25×25 m plots.

(a) (b) (c)

Fig. 2: UAV orthomosaic panels of the Selamat River corridor: (a) Segment 1 (4 panels), (b) Segment 2 (8 panels), and (c) Segment 3 (partial coverage; plot-only context). Corridor-scale cover metrics are reported for Segments 1-2 only.

Aerial imagery was processed via a photogrammetry workflow to generate high-resolution orthomosaics and Digital Surface Model (DSM) products. Here, orthomosaics are analyzed as high-resolution rasters to derive cover metrics; DSMs are treated as visual proxies to read relative surface structural heterogeneity rather than absolute canopy height estimates.

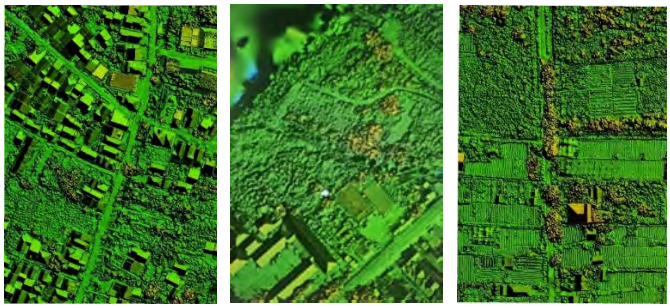


Fig. 3: UAV derived DSM shaded-relief examples used as qualitative proxies of relative surface roughness and structural heterogeneity (not absolute canopy height)

Cover metrics estimation derives the proportion of vegetation, built/impervious, bare/soil, and water/shadow classes on sample panels. Since input is RGB-based, the water class may capture dark areas/shadows; results are therefore cross-checked with visual interpretation of the orthomosaic. We also report corridor metrics per segment: (i) riparian vegetation corridor width, (ii) cover composition, and (iii) simple fragmentation indicators (e. g., patch/gap).

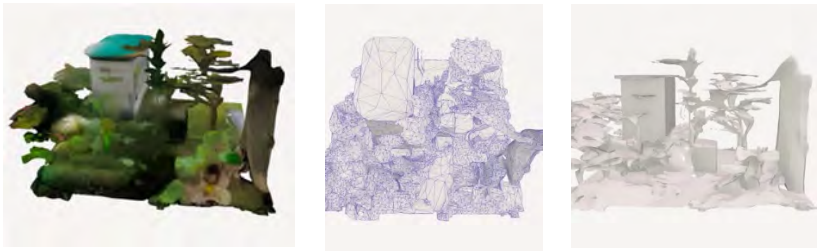
RGB classification used a simple vegetation index and brightness rules; water/shadow was cross-checked visually to reduce misclassification.

3.5 Smartphone LiDAR-Like Scans and Field Vegetation Plots

We scanned representative riparian patches with Polycam (LiDAR-equipped smartphone) to produce meshes/point clouds as qualitative proxies of local 3D structure supporting UAV interpretation (not CHM equivalents; Figure 4).

Inside or adjacent to the 3D scan patches, we established 25 × 25 m vegetation plots. In each plot, individual trees were recorded, identified by local name, and matched to scientific names where possible. We calculated the Shannon-Wiener diversity index (H′) for each plot based on species proportions.

H′ values are summarized per segment as an indication of vegetation diversity variation along the corridor and read alongside structural metrics (3D scans) and cover metrics (UAV) to build an integrated reading of riparian quality in sampled patches.



(a) (b) (c)

Fig. 4: Example Polycam outputs from one riparian patch: (a) textured mesh, (b) wireframe mesh, and (c) point-cloud/shaded view, used as qualitative 3D structure proxies

3.6 Social Context and Local Knowledge: Rapid Qualitative Insights Along the River

Beyond biophysical data, we collected brief semi-structured conversations with residents to label segment-level social functions, perceived change, and problem locations. These rapid insights contextualize priority outputs but are not treated as a full social dataset.

3.7 Deriving Preservation and Restoration Priority Zones

Zoning units were defined at the segment level. Corridor-scale cover metrics were computed only for segments with complete UAV panel coverage (Segments 1-2), while Segment 3 is treated as a plot-only segment providing biodiversity signals (H′) without corridor-scale cover metrics. For each segment we compiled three indicator groups: (1) vegetation structure/quality (e. g., corridor width, UAV cover metrics, patch structure), (2) pressure and accessibility (e. g., proximity to settlements/roads, built/bare proportion), and (3) social value and local risk (e. g., high social function, problem locations). Quantitative indicators were normalized (min-max) and categorical indicators binarized, then integrated through a rule-based overlay to produce preservation/restoration priority outputs for decision support (rather than auto-zoning). To keep the overlay reproducible, the multi-source indicators were translated into explicit decision rules (Table 2), with 'high/low' categories defined using the inter-segment distribution of available UAV-derived values (Segments 1-2). Segment 3 is interpreted through plot-based H′ and field observations until complete UAV panels are available.

Table 2: Decision rules for preservation/restoration priority categories (rule-based overlay). High/low thresholds follow the inter-segment distribution of available UAV-derived values (Segments 1-2).

Priority category	Rule (indicator logic)	Planning implication (what to do)
Preservation priority (Segments 1-2)	Vegetation cover = high AND built cover = low–moderate AND plot-based ecological quality (H′) = higher	Protect belts; prevent encroachment; manage access.
Restoration priority (Segments 1-2)	Vegetation cover = low OR built/bare exposure = high (often with observable bank exposure or corridor narrowing)	Widen belt; fill gaps; stabilize banks; manage access.
Mixed / transition (Segments 1-2)	Intermediate values OR strong within-segment heterogeneity (e. g., alternating vegetated and open/built patches)	Targeted patch restoration + protect remnants; phase actions.
Plot-only restoration signal (Segment 3)	UAV panels incomplete; use plot-based biodiversity (very low H′) + field observations to flag a restoration need	Flag restoration need; prioritize UAV completion.

4 Results

4.1 Landscape and Settlement Mosaic Along the Selamat Corridor

At the landscape scale, the Selamat River corridor reveals a land-use and settlement mosaic following the river course, characterized by varying proximity between riparian vegetation,

gardens, and built structures. While some sections remain dominated by riparian vegetation and mixed gardens, others exhibit land clearing and settlements encroaching on the riverbank. Because Segment 3 lacks complete UAV panels, corridor-scale cover metrics and overlay-based zoning results are presented for Segments 1-2 only. Segment 3 is discussed through plot-based biodiversity findings.

To quantify these patterns, cover metrics were derived from UAV orthomosaic panels in the two fully documented segments (Segment 1: n = 4 panels; Segment 2: n = 8 panels). This analysis yields relative proportions of vegetation, built, and bare cover used to read settlement-agro pressure gradients along the corridor.

Table 3: UAV orthomosaic-based cover metrics for segments with complete UAV panels (Segments 1-2)

Segment	n tiles / sample points	Vegetation cover % (mean; min-max)	Built cover % (mean; min-max)	Bare/soil cover % (mean; min-max)	Water/shadow % (mean; min-max)
1	4	35.4; 31.6-39.1	51.4; 43.4-59.5	9.9; 5.1-15.6	3.3; 2.3-4.0
2	8	48.6; 30.7-72.8	37.0; 16.2-49.4	11.9; 5.4-33.4	2.5; 1.5-4.4

Table 3 shows a built-vegetation contrast between Segments 1-2, indicating a settlement-agro pressure gradient along the corridor.

4.2 Riparian Corridor Structure from UAV and Satellite Indicators

UAV data reveals clear riparian corridor structure variations between segments. High-resolution orthomosaics allow identification of belt width, continuity, and vegetation fragmentation patterns at the river edge.

Segment 1 shows a structure more pressured by settlements and open land, reflected in lower vegetation cover and the dominance of built elements. This appears as a narrowing and discontinuous vegetation belt, with many riverbanks bordering directly on yards, roads, or built surfaces.

Conversely, Segment 2 displays a greener and more heterogeneous mosaic with higher vegetation cover, despite being interspersed with panels showing prominent land clearing at certain points. This aligns with a corridor configuration composed of mixed gardens, open plots, and riparian vegetation clumps.

UAV-derived DSMs serve as visual proxies for three-dimensional structure to distinguish dense canopy from open areas without claiming absolute canopy height.

4.3 Local 3D Structure and Vegetation Diversity from Smartphone LiDAR-like and Plot Data

At the micro scale, smartphone-based 3D scanning reveals vertical vegetation structure complexity variations between riparian patches. Vegetation plots placed around scan patches reinforce this variation through diversity metrics.

Shannon-Wiener (H′) index values show inter-segment variation based on plot data: Segment 2 tends to show higher H′ values than Segment 1. Meanwhile, Segment 3 contributes as a plot-only segment and is therefore discussed primarily through plot-based biodiversity findings without linkage to corridor-scale cover metrics. Here, diversity metrics are treated as ecological quality indications to be read alongside local pressure and spatial configuration rather than as single measures of riparian condition.

4.4 Socio-ecological Characterization of Riparian Segments

Field observations and brief conversations indicate that built-pressured segments function as multi-use riverfront spaces (water access, mooring, domestic activities) and are more prone to bank exposure, whereas greener segments are maintained for shade and bank protection but still contain access-related openings.

4.5 Priority Zones for Preservation and Restoration

Based on combined ecological and social indicators, Selamat River corridor segments are classified into preservation and restoration priorities. These categories are derived explicitly from three traceable variable blocks: (i) ecological cover (UAV-based vegetation cover), (ii) ecological quality (plot-based H′ indication), and (iii) social exposure (built cover as settlement pressure proxy).

Segments with relatively high vegetation cover and ecological quality are treated as preservation candidates. Segments with low vegetation cover, high built pressure, or prominent bank exposure are treated as priority restoration candidates. Category thresholds are set based on inter-segment value distributions to ensure transparency and traceability.

Segment-level priority labels reported here follow the explicit decision rules in Table 2; Segment 3 is discussed as a plot-only restoration signal due to incomplete UAV panels.

Table 4 summarizes segment-level priority labels with brief rationales; UAV cover metrics are available for Segments 1-2, while Segment 3 is interpreted as a plot-only restoration signal.

Table 4: Segment-level preservation/restoration priority labels with brief rationales (Segments 1-2 UAV-based; Segment 3 plot-only signal)

Segment	Vegetation cover means (%)*	Built cover mean (%) *	H′ (plot-based)	Priority label	1-line rationale
1	35.4	51.4	0.577	Restoration priority	High built exposure; fragmented belt – restore gaps and stabilize banks.
2	48.6	37.0	1.61	Preservation priority	Higher vegetation + H′ – protect belt; manage sensitive access points.
3	–	–	0.026	Restoration (plot-only signal)	Very low H′ near mouth – phase restoration; prioritize UAV completion.

*Vegetation cover and Built cover are calculated from UAV panels, thus available only for segments with complete panel coverage (Segments 1-2).

These priority outputs are positioned as a starting point for planning negotiation rather than a final decision closing local deliberation. This summary allows readers to view explicit zoning outputs at the segment level, even if a full map visualization is not included in the main text.

5 Discussion

Limitations include incomplete UAV panels for Segment 3, RGB shadow-water ambiguity in classification, and field constraints that limited replication; rapid qualitative insights remain contextual.

5.1 Reading Riparian Health in a Data-Poor Tropical River

Integrating satellite imagery, UAV mosaics, smartphone-based LiDAR-like scanning, and vegetation plot data reveals that the Selamat River riparian corridor is in a moderate but fragile condition, with distinct inter-segment contrasts. The two segments with complete UAV coverage show a clear divergence between areas under intensive settlement pressure and those retaining a vegetation-agro mosaic.

As summarized in Tables 4-5, Segment 1 is built-pressured with constrained riparian vegetation, while Segment 2 retains higher vegetation cover and stronger patch heterogeneity.

Plot-based biodiversity signals reinforce this contrast: H′ is highest in Segment 2 and lowest in Segment 3 (plot-only), indicating that ecological quality cannot be inferred from cover alone.

These findings align with tropical agricultural landscape studies showing riparian belts as key buffers for biodiversity and water quality in converted mosaics.

5.2 Methodological Contribution: Low-Cost Cross-Scale Digital Workflow

This study develops a cross-scale workflow for data-poor tropical rivers that links Sentinel-2 context, UAV RGB orthomosaics (with DSM as a relative proxy), Polycam-based local 3D cues, and plot-based Shannon diversity (H′). Unlike single-scale satellite mapping or high-cost airborne LiDAR campaigns (NONES & GUERRERO 2019, PU et al. 2021, GUO et al. 2021, CHEN et al. 2025), it emphasizes transparent, rule-based priority outputs that can be revisited and renegotiated with stakeholders.

5.3 Working with UAV and Smartphone LiDAR in Resource-Limited Settings

Field experience shows that adopting UAVs and smartphone LiDAR-like tools is shaped as much by logistics and operating conditions as by technical specifications. UAVs enable kilometer-scale coverage in hours at a resolution sufficient to distinguish buffers, gardens, and settlements, but data quality depends on weather, wind, access to takeoff points, and local permission contexts. At the micro scale, Polycam complements UAV observations by providing relative 3D structural cues; while consumer-grade sensors can generate useful point

clouds for comparative monitoring, absolute accuracy remains limited and scanning requires stable movement paths and careful file handling in challenging field conditions (ALIJANI et al. 2022, BALESTRA et al. 2024, SAE-NGOW et al. 2025). For budget-constrained institutions, this combination offers a pragmatic balance between cost and information depth and can support communication with local stakeholders through intuitive 3D visualizations.

5.4 Socio-Ecological and Governance Implications for Riparian Restoration and Planning

Uniform buffer standards can trigger conflict when settlement history and access rights are ignored, reflecting biodiversity-livelihood trade-offs in Southeast Asian riparian settings (TAN et al. 2022, MITCHELL et al. 2018). Segment 1 illustrates this tension: high built exposure coincides with high need for bank protection, yet restrictions are socially costly without viable alternatives. In Indonesia, restoration feasibility is strongly shaped by governance: responsibilities for riparian management are fragmented across agencies, enforcement is uneven in linear settlements, and tenure/use rights complicate uniform setback prescriptions.

In this context, the workflow functions not only as a diagnostic tool but as decision support for negotiated, staged interventions. Cross-scale outputs (cover metrics, plot-based biodiversity signals, and 3D visual cues) can help make pressures and ecological signals legible enough to discuss feasible actions – such as restoring gaps, protecting remnant belts, and redesigning access – when embedded in collaborative planning processes (REILLY & WILLENBOCKEL 2010, ANSELL & GASH 2008). Used in village deliberations or district planning forums, these outputs can act as digital boundary objects: priority labels can be tested against local knowledge (e. g., floods, boat paths, and critical sites) and iteratively translated back into revised criteria, helping avoid restoration that is technically "correct" but socially unworkable.

5.5 Implications for Riparian Corridor Design and Planning

These outputs support design by distinguishing preservation candidates from restoration priorities using auditable indicators, intended as a basis for contextual planning rather than rigid zoning.

6 Conclusion

The Selamat River riparian corridor contains both higher-value patches and segments degraded by settlement and agricultural expansion. Integrating satellite imagery, UAV mosaics, smartphone LiDAR-like scans, and plot-based Shannon diversity signals enables cross-segment comparison and the derivation of transparent preservation/restoration priority outputs. Methodologically, the workflow is inexpensive and replicable, linking plots and 3D patches to UAV segments and satellite context using accessible tools. The primary value lies in providing transparent, traceable evidence for planning in data-poor rivers, while remaining effective only when coupled with inclusive, context-sensitive governance.

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Flood Sandbox: Participatory Planning Through Digital Gamification

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Abstract: This research examines innovative approaches to participatory planning through the frameworks of gamification, procedural generation, and data-driven visualization. With the development of a Flood Sandbox, an interactive platform for data-driven landscape and flood risk visualization in coastal Louisiana, we propose a democratized community engagement process that enables the co-production of knowledge, priorities, and decisions through scenario-driven evaluation. By creating a digital environment for collaborative decision-making, planners and stakeholders can engage in rich conversations to develop data-driven planning scenarios in real time. This gamified interaction loop can increase trust in the planning process, leading to more transparent communication and informed decision-making.

Keywords: Participatory planning, generative visualization, decision support

1 Introduction

In complex planning projects, decision-making is difficult. A plethora of constraints and far-reaching consequences make problem-solving a sensitive and challenging duty that must be data driven. At the same time, valuable planning data is often locked in complex geospatial datasets, making it difficult to interpret. Using existing GIS technologies for this increases project complexity for planners and can make community engagement difficult (Luo et al. 2025). Our work aims to address this gap by proposing a system design that visualizes geospatial data and facilitates the scenario-based, co-productive evaluation of planning decisions. This platform integrates visualization and simulation technologies commonly found in video games with geospatial data interpretation to create a virtual environment (Figure 1) for developing and comparing coastal planning approaches, empowering planners and their stakeholders (Bai & Hew 2025).

The importance of scenario planning in the field of built-environment design is well documented. It helps planners make decisions that are feasible within design constraints and in line with a community's will by engaging in a comparative and collaborative process that evaluates multiple options. This approach provides an alternative to top-down approaches (Dandridge & Montalvo 2024). By analyzing geospatial and community data, planners can develop targeted scenarios to address perceptual and material challenges. These scenarios can then be used as tools for conversations with stakeholders, especially when visualized. When integrated with simulation, this practice enables planners to compare the projected outcomes of their options and assess the impact of their decisions. This project sits within a broader co-creation approach, positioning itself as a collaborative stage that can fuel the joint development of ideas, decisions, and knowledge among planners and stakeholders alike.

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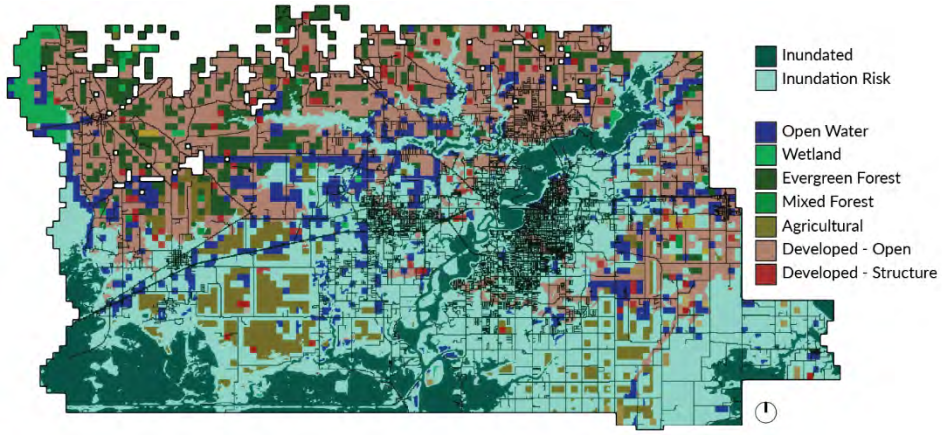

Fig. 1: Scene generated by the Flood Sandbox prototype

Digital twins are a landmark example of such an interpretive system. As virtual simulations tied to real-world sensor data (King 2025), they are crucial tools for predictive analysis and decision-making in urban and industrial systems (Lăzăroiu et al. 2024). Increased access to computing power and high-resolution data (Jiang et al. 2021) has prompted a surge in their use and popularity. We draw on the robust set of approaches outlined by digital twins to construct our system. However, the Flood Sandbox differs in that it uses static datasets. Our approach, which serves more as a snapshot in time, prioritizes computational feasibility and addresses the lack of dynamic sensor data in our study area, while providing planners with lag time to vet the datasets that drive the Sandbox's decision-making functions.

Another key component of our approach is gamified interaction. Broadly speaking, gamification refers to the application of game-style mechanics and reward systems in non-gaming contexts (Sandbrook et al. 2025). By adapting the gamification model used in Catch the Bus, a travel training application (Decoito & Briona 2025), we can allow planners to interactively construct and compare coastal flooding across planning scenarios. Catch the Bus uses a three-tiered gamification model: dynamics, mechanics, and feedback (Decoito & Briona 2025). Dynamics guide the game, mechanics create gameplay interactions, and feedback rewards players. We applied this framework to our approach (Table 1) and developed it further with a real-world case study.

We guided the development of the Flood Sandbox through a case study in Calcasieu Parish, Louisiana. The Parish sits on the southern edge of Louisiana, just 30 miles from the state's coastline. The entire parish is at very high risk of flooding while also facing residential and industrial development interests. Mitigating this risk while maximizing buildable land area is an ongoing challenge in the parish, especially when accounting for green infrastructure interventions and other sustainable initiatives. Devising equitable solutions requires extensive, highly sensitive study (Dandridge & Montalvo 2024). This challenge presents an ideal use case for our participatory planning tool. By combining geospatial data and interactive mechanics, we can create a Flood Sandbox for Calcasieu Parish. This project is still ongoing, and as such, our approach is still in development. This paper describes the current state of the Sandbox, which will serve as the basis for future expansion.

Table 1: Implementation of gamification elements within the Flood Sandbox

Gamification element	Implementation
Dynamic	In-game currency, spatial constraints
Mechanic	Flood intensity, simulated side effects of user decisions
Feedback	Scenario-based metric scoring

2 Data and Methods

2.1 Source Data

To construct the Flood Sandbox for Calcasieu Parish, we first assembled a dataset to drive a procedurally generated digital representation of the built environment (Table 2). In our case study, this data included a digital terrain model, vector-based geospatial data, and raster-based data outlining land usage and flood depths. This assemblage of information has the potential to yield valuable insights into the intensity of flooding throughout the parish, and which types of structures and landscapes are most susceptible to damage (LUO et al. 2025).

Table 2: Summary of data sources

Dataset Type	Data Source	Format/Resolution	Use in Sandbox
Terrain (DTM)	USGS LIDAR 1/3 arc-second	Raster, 10m	Elevation mesh generation
Buildings	CPRA Inventory	Vector	Procedural building placement
Roads	LADOTD Statewide Routes	Vector	Roadway placement and volume visualization
Flood Inundation	CPRA Flood Depth Dataset	CSVs for 10, 50, and 100-year storms	Collision-based inundation logic
Land Use	USGS NLCD 2023	30m	Cell attribute assignment

2.2 Game Engine Integration

Once we assembled our dataset, we needed to build an environment to parse, manipulate, and visualize it. In line with our conceptual framework of gamification, we opted to use a game engine rather than GIS or 3D modeling software. This is because game engines are uniquely suited to perform the rapid logic-based computation that our system requires (CHAMPION 2021). Similarly, they are well-suited for the real-time visualization of large geometric datasets. Finally, we needed any gamified system we developed to be redistributable across potential users' computer systems. Game engines enable us to build our system into executables for a wide range of mobile, desktop, and web platforms. We chose to work with the Unity engine because of its customizable backend, which enabled us to use external geospatial data parsing libraries (HARRAP et al. 2019).

2.3 Modeling Methodology

Due to the large size of our geospatial dataset, we opted to procedurally generate a landscape model in Unity using raster-based location mapping techniques (YAN et al. 2025). While this

produces a visualization, the generated geometry also drives core simulation mechanics. Land-use tiles, building volumes, and roads are converted into 3D geometry in the Unity engine, transforming them into agents that are "aware" of their attributes and those of their neighbors (Figure 2). All procedural geometry is generated in a grid. Elevation and land use rasters form the base cells, while buildings and roads are placed on top. Inundation is calculated per cell using meshes assembled from rasters encoding flood depths across the parish under different scenarios. Each cell casts a ray upward from its median elevation; if the ray intersects the inundation mesh, the Sandbox records the cell as inundated. This grid-based pattern is optimized for simulation while allowing planners to symbolize land-use, elevation, and inundation data in a manner similar to traditional GIS solutions.

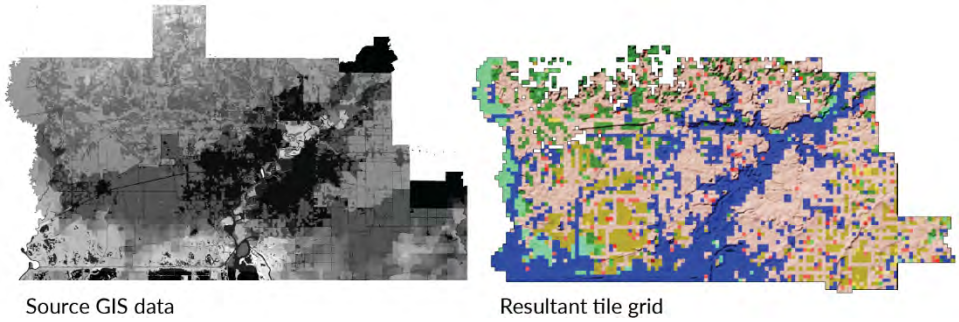

Fig. 2: Source GIS data and resulting procedural generation tiles

2.4 Interaction Design

Gamified interaction expands our system's capability to encompass planning and analysis. Once the dataset model is procedurally generated, users can select tiles and propose predefined project types within them (Table 3). We opted for a cell-based siting approach rather than specifying actual locations to accelerate inundation calculations and scenario scoring. Each project in our case study mirrors a typical kind of development project in Calcasieu Parish. Their effects on the overall model mimic what they might do in the real world. For example, a "residential development" project reduces the inundation level of its corresponding cell but increases the inundation levels of the surrounding cells. In the same manner, a "wetland conservation" project reduces the inundation level of nearby non-wetland cells. However, it would make it impossible to build anything else on that cell in the scenario.

Table 3: Predefined project types. Cost, benefits, and side effects are placeholder values used to test the system

Project type	Simulated cost	Simulated benefit	Simulated side effect
Structural Levees	$10 million	Significantly reduces inundation on its tile	Increases the inundation on surrounding tiles
Green Infrastructure	$2 million	Moderately reduces inundation on its tile	Slightly reduces inundation on surrounding tiles
Wetland Conservation	$5 million	Reduces inundation across the tile grid	Prevents further development on its tile
Residential Elevation	$7 million	Reduces structural inundation on its tile	No effects on other tiles

Scenario constraints include a fixed budget set by users at the start, with each project costing in-game currency based on real-world prices and requiring a certain amount of space. Only a limited number of projects fit in each cell, narrowing choices. Choosing a project like 'wetland conservation' means sacrificing others like 'structural levees' due to budget limits, encouraging users to balance their values and planning goals. All scenario definitions are made through a simple dropdown menu in the Sandbox.

2.5 Scenario Scoring

The tool evaluates user scenarios by measuring cell inundation, development, and flooded structures or roads before and after proposals. Calculations use specific formulas (Figure 3), and scores can be exported as a CSV. A composite score C_s summarizes flood resilience in points out of 100, with higher scores indicating greater resilience. The composite scoring system is based upon the following formula, whose variables are calculated programmatically by the Sandbox.

$$C_s = stability \times diversity \times (1 - development\ pressure)$$

Stability is the number of tiles that did not change between existing conditions and the proposed scenario. Diversity measures the distribution of land cover classes and its regularity. Development pressure represents the net change in the number of developed tiles within a scenario. A high-scoring (and thus, resilient) scenario is highly stable and diverse, with very low development pressure. Component scores are also available to users of the Sandbox for further analysis.

3 Results

The digital landscape model generated by our procedural generation methodology is a simplified, abstracted version of a real-world landscape, serving as a venue for flood simulations and interactive, participatory planning. This environment also provides the necessary data structure to drive a gamified, simulation-driven analytics engine. In its current form, our Flood Sandbox can use collision logic to determine the distribution of structural inundation under 10-, 50-, and 100-year design storms, as well as the impacts of various development projects on those storms. It is important to clarify that while this collision-based system does not replace high-fidelity hydrodynamic engineering models (e. g., HEC-RAS), it functions as a close-enough heuristic tool. Its primary goal is to provide immediate, data-driven visual feedback that catalyzes real-time participatory dialogue.

To demonstrate the data the system can currently output, we ran three scenarios to compare their metric scores (Table 4). We also used the visualization tools within the Sandbox to generate map-style land-use plots, which could be used in community engagement contexts (Fig.3). In addition to a base scenario run using the sandbox's core data, we created two scenarios: one focused on maximizing resilient strategies, and another prioritizing the creation of new housing. Based on our scoring methodology, we could compare the performance of each scenario and summarize its overall impact.

Table 4: Metric score comparison

Scenario priority	Change in percentage of inundated cells (100-year storm)	Change in percentage of cells that are developed	Scenario score	Scenario summary
A: No change	0	0%	53.9	Illustrates existing conditions.
B: Resilient strategies	-18.3%	-16.5%	61.5	Highlights the sweeping impact that resilient strategies can have on inundation.
C: Maximized development	+9.2%	+11.8%	43.2	Highlights how overabundant residential development can increase overall inundation.

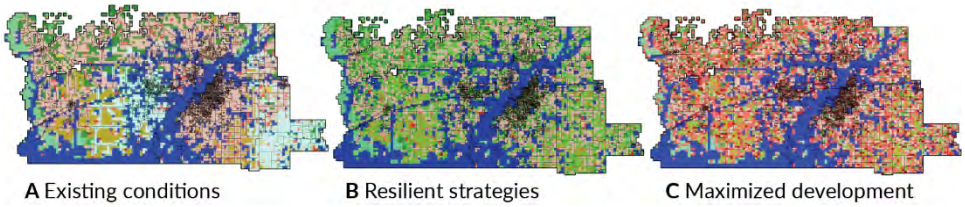

Fig. 3: Scenario Maps. See Figure 1 for legend.

4 Conclusion and Outlook

The integration of data-driven visualization techniques, gamified elements, and procedural landscape representation into an interactive platform can enable planners to make their process more transparent to their stakeholders, particularly in coastal contexts (Luo et al. 2025). By combining geospatial data, user input, and simulations of dynamic landscape phenomena, such as flooding, we can construct a digital Flood Sandbox to support data-driven planning decisions, promoting equitable, sensitive decision-making rooted in co-production. This sandbox fuses the digital twin-style representation of real-world landscapes with targeted, intelligible abstraction, distilling complex challenges of land use and infrastructural intervention into digestible virtual scenarios.

At present, no directly comparable flood sandbox approaches have been identified, which limits direct comparison in this study. As similar methods emerge, future work will be able to more systematically evaluate and benchmark this approach. As we further develop the Flood Sandbox, the system is currently undergoing expert validation with a cohort of planners to assess usability. Our first focus group includes the floodplain managers, coastal planners, and governmental officials who may eventually deploy this tool in their decision-making processes. With them, we aim to develop the sandbox's user interface further and incorporate additional features to enable more advanced analytical visualizations.

By embedding co-production across all phases of the project, the Flood Sandbox demonstrates how collaborative design processes can function as both a methodological framework

and a mechanism for broader impact. As a result, this approach opens new pathways for the democratization of planning and reconfiguration of existing community engagement processes.

Acknowledgements

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Ecosystem Services, Biodiversity and Ecological Networks

Toward Urban Forest Resilience: An Application for Assessing and Comparing Local Level Urban Street Tree Diversity and Equity

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Abstract: This paper examines how existing data limitations and approaches to assessing street tree biodiversity and age diversity constrain our ability to plan, design, and manage equitable and resilient urban street tree systems. In response, we developed an open-source R-Shiny data pipeline and provided recommendations to strengthen data consistency and comparability. Applying this application to street tree programs in 26 U.S. cities reveals significant variation in biodiversity outcomes and highlights the need for targeted investment. Our approach supports more strategic planting decisions, prioritizes vulnerable neighborhoods, and strengthens long-term urban forest resilience under climate change by directing planting, maintenance, and monitoring resources to neighborhoods falling below resilience-oriented benchmarks.

Keywords: Street trees, biodiversity, equity, data science, urban forest resiliency

1 Introduction

This paper describes how past and current efforts to analyze the biodiversity and age diversity of street trees are limiting our ability to understand, plan, and design a robust, equitable, and resilient street tree system. Our focus on biodiversity benchmarks and spatial disparities draws on established work linking ecological resilience to functional and structural diversity, and social resilience and environmental justice to the uneven distribution of environmental burdens (HOLLING 1973, SCHLOSBERG 2007). While our analysis is empirical, these theoretical perspectives frame the relevance of our metrics for understanding vulnerability and adaptive capacity in urban forests. To facilitate a better understanding of trends in tree diversity and the role that different types of street tree programs play in these efforts, we developed an R Shiny data pipeline. Our efforts underscore the need for standardized data collection and analysis. Thus, we recommend strengthening and standardizing tree inventory data and have developed an open-source pipeline to analyze biological and age diversity. We conclude by presenting the results of our analysis and comparison of the effectiveness of street programs of twenty-six U.S. cities.

Street Tree Diversity Benefits and Benchmarking

Street trees are indispensable components of urban forests and nature-based solutions (NbS), providing critical ecosystem services including carbon sequestration, urban heat mitigation, stormwater management, pollution filtration, and habitat provision (COLEMAN et al. 2022). Beyond providing essential ecosystem services, street trees also define the spatial qualities

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of a streetscape by delimiting the pedestrian realm, calming traffic, filtering sunlight, providing visual order, and introducing beauty (SMART et al. 2020). Given the breadth of services and spatial qualities that street trees provide, they are crucial elements of livable cities (LAWRENCE 2008, MASSENGALE & DOVER 2013). Yet, urban trees are in decline due to multiple stressors that undermine these benefits while exacerbating environmental inequities in access to services (HOFFMAN et al. 2020, WONG et al. 2021).

Numerous researchers and practitioners have documented how a lack of tree diversity endangers urban forests, due to biotic and abiotic stressors (MORGENROTH et al. 2016, PLANT & KENDAL 2019). For example, in the United States, over the last century, many communities have lost their street trees and their associated benefits due to the near monocultures of American elm (*Ulmus americana*) within many communities, caused by Dutch elm disease (DED, *Ophiostoma ulmi*) and, more recently, elm yellows (*Candidatus Phytoplasma ulmi*) (HAUER et al. 2020, ROMAN et al. 2018). Communities often replaced elms with ash trees because they had similar growth requirements and both provided substantial shade, making them ideal for tree-lined streets. However, the invasion of the emerald ash borer (EAB, *Agrilus planipennis*) has prompted renewed discussions on tree diversity and how a lack of diversity can have substantial consequences for the continuity of tree services (HAUER et al. 2020, MA et al. 2020).

Communities adopted a shift to numerical quantification of tree diversity, intending to reveal the potential impacts of stressors and enable communities to pre-emptively mitigate catastrophic economic and environmental degradation (MA et al. 2020). The most common benchmarks are based on a percentage system that uses the relative abundance of trees at various taxonomic levels, including species, genus, and family. Santamour (1990) popularized the 10/20/30 (species/genus/family) rule.

In contrast, LEFF (2016), BALL & TYO (2016), and others argued for a stricter rule of 5/10/15. While these two benchmarks provided a means of understanding street tree diversity, additional research suggests that each community should develop internal limits and benchmarks aligned with management goals (ORDONEZ et al. 2014, SIMONS & HAUER 2014). Researchers have also used measures such as richness, evenness, Shannon index, Simpson's index, and the inverse Simpson's index to assess tree diversity. However, in contrast to previous rules, while these indices have been widely adopted for comparing across landscape types (e. g., urban, suburban, rural), typically they have not been widely adopted in American urban forest practice, as they can be more challenging to calculate and interpret, sensitive to sample size, and are complex to translate into design and planning policy targets (MA et al. 2020).

Taken together, benchmarks and biodiversity indices are complementary: taxonomic benchmarks translate biodiversity goals into clear, actionable guidance for species selection at the site and project scale, supporting day-to-day planting decisions. Diversity indices, meanwhile, reveal broader spatial patterns and deficiencies, helping practitioners and policymakers target planting programs and policy interventions where biodiversity is most limited, thereby strengthening overall urban forest resilience.

The benchmarks and indices above assess the resilience of species, genera, and families but do not comprehensively evaluate the long-term health, resilience, and function of urban forests. An unevenly aged urban forest is just as much of a concern as one that lacks biodiversity. A balanced mix of young, mature, and old trees ensures continuous canopy cover, maintains a variety of ecosystem services, and provides stable habitats and psychological benefits for

the community. Without diverse age classes, urban forests become vulnerable to stress, disease, and the eventual loss of canopy when large, old trees decline. To address age diversity, Richards (1983) suggested using the 40/30/20/10 rule based on the diameter at breast height (DBH) of trees (Tab. 1). While imperfect, as not all tree species exhibit consistent trunk growth as they age or reach their ultimate trunk size, it does provide a crude means to assess age diversity at scale, which is fundamental for effective governance and management of street tree populations. In this context, "strategic biodiversity investment" refers to allocating planting and management resources to areas where benchmark deviations indicate heightened vulnerability. These metrics also support design and planning workflows by informing species-selection decisions, age-class balancing, and spatial planting strategies aligned with resilience goals.

Table 1: Richards' (1983) 40/30/20/10 age benchmark with associated

Age Class/Maturity Stage	Average Size DBH	DBH Ideal Distribution
Juvenile	0-8"	40%
Semi-mature	>8-16"	30%
Mature	>16-24"	20%
Senescent	>24"	10%

Previous Diversity Assessment Efforts

Numerous previous studies on street tree diversity have employed the aforementioned benchmarks and indices. Early studies, such as those by Beatty and Heckman (1981), examined 177 cities and found that 42% lacked statistics on their tree management activities, suggesting the need for more comprehensive data collection. Landry and Chakraborty (2009) used remote sensing to identify the inequitable distribution of tree cover. They found that low-income minority communities have less tree cover in public rights-of-way within the United States (LANDRY & CHAKRABORTY 2009). While McCoy et al (2022) focused on inter-city data analysis across many cities, more recent studies took two forms: large "n" cross-city comparisons of biodiversity, or those examining within-city biodiversity and equity (COWETT & BASSUK 2017, KENDAL et al. 2014). Studies that conduct cross-city comparisons of biodiversity, age, and equity are challenging due to inconsistent data or the absence of critical attributes, such as DBH. As a result, most studies are conducted at the metropolitan scale rather than at sub-metropolitan scales, further limiting the scope of longitudinal research and deeper understandings of tree equity.

Street Tree Governance and Management

Within the United States, there is no single national legal definition of a "street tree," nor is there a single agreed-upon research definition. Street trees are subject to local municipal ordinances that vary by city, town, and county. However, despite these legal and research variations, each definition typically requires that the tree be outside private property, near a street, and within the public right-of-way. We focus on street trees because they are the most prominent component of urban tree planting initiatives, account for the largest share of urban tree expenditures, and, despite making up only 10% of urban trees by population, account for 25% of leaf area (SMART et al. 2020).

Cities have developed a variety of street tree governance programs, often spanning multiple administrative units and the private sector. For example, in San Francisco, CA (U.S.), street trees were once the responsibility of the adjacent property owner, effectively privatizing their installation, maintenance, and removal. However, in 2016, a new policy returned street trees to public responsibility (San Francisco Street Tree Ordinance 2017). Yet, other cities have public/private partnerships for planting, maintenance, and removal of trees (e. g., Indianapolis, IN (U.S.)). There is further nuance even within publicly governed programs: some are distributed across multiple organizations within the city, while others are housed in a single department. The host departments included the Division of Public Works, the Department of Transportation, the Department of Parks and Recreation, the Department of Forestry, and the Planning Department. Whether a program is private, public, or a combination of both is crucial because it can lead to significantly different objectives and street tree priorities (COLEMAN et al. 2022). Likewise, the public governance structure could create different and competing programmatic priorities (COLEMAN et al. 2022). While this paper focuses on cities in the U.S., the privatization of urban forests, the inequitable distribution of tree cover, and tree biodiversity are of global concern (ÅKERLUND et al. 2006, PENA et al. 2024, ŻUK & ŻUK 2021).

A review of the literature indicates that very few studies have evaluated the governance types of street tree programs. Of the few existing studies, only a small number studied cities in the United States. These studies were either geographically limited to small "n" case studies or focused on tree survival or on outcomes of tree program participation (ROMAN et al. 2015, WIRTZ et al. 2021). Thus, making extensive cross-city comparisons of program type, age, and biodiversity outcomes difficult. This gap is problematic, as it impedes understanding of the role that governance structures play in establishing a robust, climate-resilient street tree system.

Existing Urban Forestry Software

Arborscope (BARTLETT CONSULTING 2025), Urban Forest Metrix (FIELD TRUTH INC 2026), iTree (I-TREE 2026), and other bespoke ArcGIS dashboard applications (e. g., TreePlotter Inventory (CITY OF INDIANAPOLIS 2025)) support individual tree location, health, and maintenance tracking, as well as calculations of tree canopy and ecosystem services benefits. However, we could not find any that address the novelty of our approach, as very few of these other applications support biodiversity or age analyses within their existing software frameworks at multiple planning scales (i.e., city, neighborhood, or census units). Moreover, most of these platforms are not structured to allow designers or planners to readily pair publicly available tree data with scenario testing or to evaluate how their species or age-class selections might influence outcomes across broader spatial units. As a result, practitioners have limited capacity to use these tools to understand the potential system-level impacts of their design choices, underscoring a gap between available urban forestry software and the analytical needs of design workflows.

Research Aims

Our study aims to address challenges identified in previous research by establishing clear data standards and developing tools that non-technical users can use to understand and analyze their street tree programs. The internal alpha test of these tools guided our investigation

of three key questions: 1) To what degree do cities exhibit biodiversity and age diversity issues? 2) To what degree is diversity equitably distributed? and 3) Do specific types of tree programs lead to better street diversity? We hypothesize that 1) the spatial distribution of urban forest age and biological diversity is linked to socioeconomic factors such as poverty and minority status, and 2) cities with quasi-public street tree programs are more equitable, biologically diverse, and age diverse.

To test these hypotheses, we conducted diversity analyses at the local scale, both within neighborhoods and at the Census tract level, and incorporated socioeconomic variables from the CDC Social Vulnerability Index (CDC/ATSDR 2020) because cities are increasingly prioritizing equity in urban forestry. We performed regression analyses to 1) understand the availability and trends in street tree species and age diversity compared to socioeconomic trends and 2) predict the outcomes of different tree programs (public, private, or public/private). Beyond these analyses, our study examined how management regimes correlate with patterns of biological and age diversity. We anticipate that this research will help planners and landscape architects shape street tree governance and policy and select trees that build a diverse and resilient urban forest system.

2 Methods

2.1 Study Area

The population for this study comprised cities in the United States (U.S.) with geolocated, publicly available street tree datasets containing scientific names and diameter at breast height (DBH). No existing list of U.S. cities meeting these criteria exists, so we compiled our own. To date, we have identified 26 U.S. cities that meet this criterion: Ann Arbor, MI; Aurora, CO; Baltimore, MD; Boston, MA; Buffalo, NY; Cambridge, MA; Columbus, OH; Denver, CO; Grand Rapids, MI; Indianapolis, IN; Jersey City, NJ; Madison, WI; Minneapolis, MN: New Haven, CT; New York City, NY; Philadelphia, PA; Pittsburgh, PA; Portland, OR; Providence, RI; Sacramento, CA; San Francisco, CA; San José, CA; Seattle, WA; St. Louis, MO; and Washington D.C.. Cities with inconsistent street tree data across the city or incomplete tree inventories were not used in this study. Future studies will continue to add more cities as they meet the appropriate criteria.

2.2 Application Development

Monitoring street tree diversity and equity is challenging due to messy data and specialized analytical requirements. We developed the Urban Forest Biodiversity Explorer (R Shiny app) to address this. Figure 1 is a flowchart outlining the application development process and general workflows. The application determines whether the top 10 planted species exceed the two diversity metrics (5/10/15 and 10/20/30) and presents the results in a bar chart. Thematic maps present biodiversity and age indices for each neighborhood. Users can upload their own data for analysis. Figure 2 shows a sample application use, the species frequency benchmark, and the neighborhood biological diversity map for New York City, U.S.

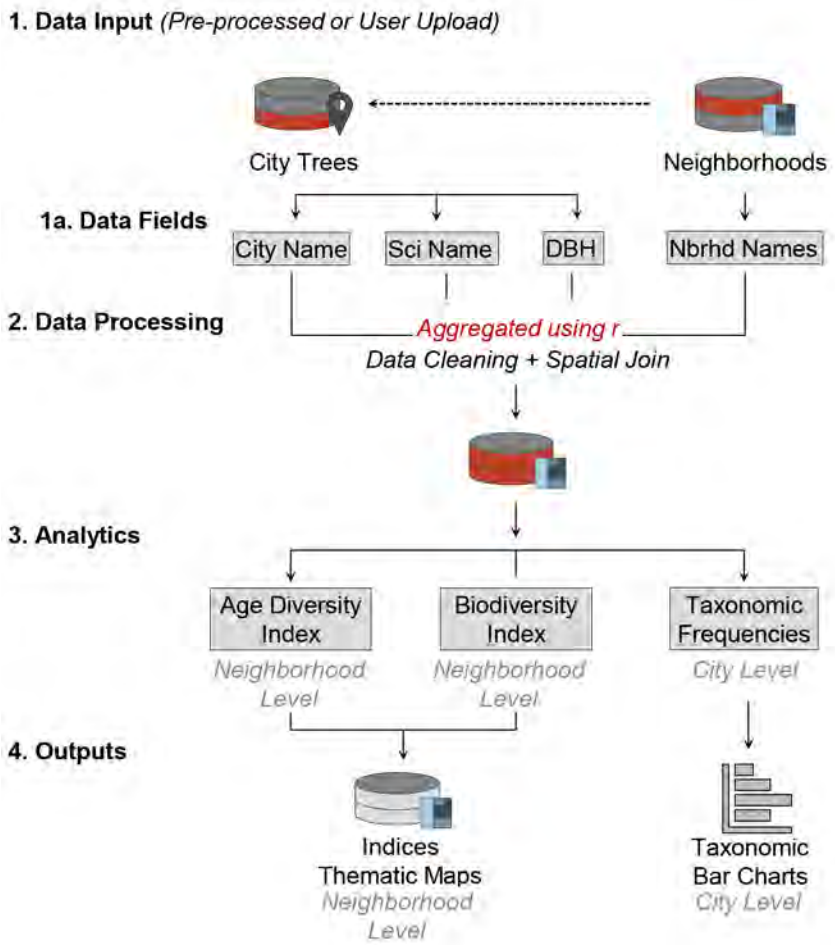

Fig. 1: Flowchart documenting a schematic of the application framework

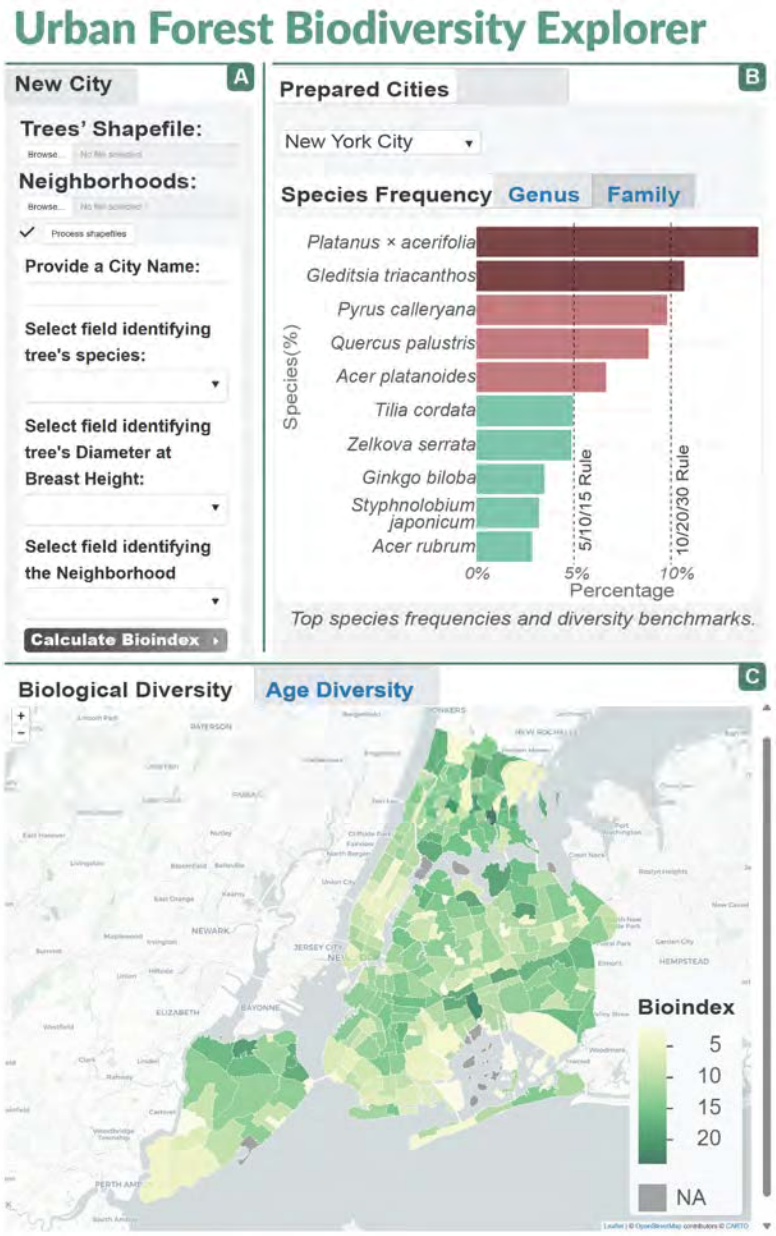

Fig. 2: Screenshots of the application illustrating species biodiversity in New York City: (a) new city data upload; (b) top ten planted species taxonomic output charts; (c) neighborhood thematic maps for biological and age diversity. Note that a supplementary video S1 of the interactive application referenced in this manuscript is available at the following link: https://zenodo.org/records/18202943?t.

2.3 Data Cleaning and Benchmark Calculations

We used R for all data cleaning and benchmark calculations. To address tree-choice decisions and identify where additional biodiversity is needed, we implemented the following benchmarks and indices: 5/10/15 and 10/20/30 biodiversity benchmarks, a 40/30/20/10 age benchmark, and an Inverse Simpson Index for our Biodiversity Index (Bioindex). The age diversity of street trees was calculated using the 40/30/20/10 rule. These benchmarks serve as practical tools for operationalizing urban forest resilience by ensuring that species and age structures are sufficiently diverse to buffer urban forests against pests, diseases, and climatic stressors. By quantifying deviations from these resilience-oriented targets, our approach helps cities prioritize interventions that strengthen long-term ecological stability. Together, these diversity and age-structure metrics function as resilience indicators by quantifying a population's capacity to withstand, adapt to, and recover from climate-driven disturbances.

We evaluated and mapped biodiversity and age diversity at the metropolitan, neighborhood, and census tract scales. The following describes the Bioindex (SHAH et al. 2021):

$$BiodiversityIndex = \frac{1}{\sum_{i \epsilon S} SpeciesFreq_i^2}$$

S is the set of species

We used the Euclidean distance between age and the benchmarks. That is, the proposed age index is the square root of the sum of the square differences between age frequency and the benchmark:

$$TreeAgeDiversityIndex = \sqrt{\sum_{i \epsilon G} (AgeFreq_i - AgeBenchmark_i)^2}$$

G={Juvenile, Semi-mature, Mature, Senescent}

2.4 Statistical Tests

This paper employs two ordinary least squares models to test the two research hypotheses. The first set of models calculates the Bioindex at the species level and the age diversity as outcome variables (Tab. 2). Predictor variables are from the CDC Social Vulnerability Index (SVI) dataset (CDC/ATSDR 2020). The second set of models tested urban forest diversity metrics as outcomes of predictor variables associated with different types of tree program governance: public, public-private, and private (Tab. 3). Control variables adopted on both model types include climate zones and census tract area. Note that Portland, OR, was excluded from the regression analyses because, during benchmarking and application development, we found that 30% of Portland's trees were identified only to the genus level.

Table 2: Summary of equity, biodiversity, and age diversity model predictor variables

Model Type	Predictors	Outcome	Control Variables
Model a	Minority Population (%), Population Below 150% Poverty (%), Households with No Vehicle (%)	Species Biodiversity	Biophysical factors: Climate zone, Census tract area
Model b	Minority Population (%), Population Below 150% Poverty (%), Households with No Vehicle (%)	Age Diversity Index – Dist. to Benchmark	Biophysical factors: Climate zone, Census tract area

Table 3: Summary of street tree program type regression model variables

Model Type	Predictors	Outcome	Control Variables
Model a	Tree Program Management Type	Species Biodiversity	Biophysical factors: Climate zone, Census tract area
Model b	Tree Program Management Type	Age Diversity Index – Dist. to Benchmark	Biophysical factors: Climate zone, Census tract area

3 Results and Discussion

Our results demonstrate how species diversity, age-class distribution, and deviations from resilience benchmarks act as indicators of an urban forest's capacity to withstand and adapt to stressors associated with climate change. Neighborhoods with narrow age structures or dominance by a few species may have diminished resilience to disturbance, whereas areas closer to benchmark targets exhibit stronger adaptive capacity. By evaluating these patterns across fine spatial scales, our study provides actionable evidence for strengthening local-level urban forest resilience.

3.1 Untidy Data and Data Stationarity

The initial city list had 79 entries, but data were often incomplete and inconsistent: many cities withheld data, tree surveys covered limited areas (often focused on city centers), critical variables (scientific name, DBH, location) were missing, and data contained inconsistent field names, outdated scientific names, misspellings, and records of dead trees or empty pits. To reduce errors, we recommend minimum standards: geolocated trees with genus, species, and DBH (all lowercase), plus routine verification against the International Plant Names Index. Additionally, we recommend a more comprehensive geographic tree inventory, as the current datasets are limited to either streets or streets and other public properties and do not include information on private trees. Finally, we recommend that datasets be version-controlled to document temporal changes, as time-series analysis is currently not feasible due to the majority of cities having incomplete, static datasets.

3.2 Descriptive Results

At the city level, none of the 26 analyzed cities complied with Leff's 5/10/15 rule. Three cities (11.5%) (Cambridge, Denver, and San Francisco) successfully met the 10/20/30 rule

(Tab. 4). Buffalo, Indianapolis, Madison, Milwaukee, Pittsburgh, and San José met the optimal age benchmark, with a tolerance of ±5% for each growth stage. When comparing our proposed Bioindex, Seattle had the highest score at 66.42. Additionally, many cities have similar top species and genera (8-*Acer platanoides*, 5-*Platanus x acerfolia*, 4-*Gleditsia triacanthos*, and 4-*Acer rubrum)*. Regionally, this is problematic as pests or diseases migrate between cities.

Table 4: City-level: tree number, and percent of species, genera, and families that breach the benchmarks, and age descriptive statistics

City (St.)	Trees	BioIdx (Sp)	Sp > 10%	Sp > 5%	Gen > 20%	Gen > 10%	Fam > 30%	Fam > 15%	Age dist.
Ann Arbor (MI)	54,118	29.49	0%	30%	29%	29%	0%	29%	0.22
Aurora (CO)	55,160	10.84	45%	58%	0%	62%	0%	37%	0.16
Baltimore (MD)	121,224	28.70	12%	28%	22%	34%	0%	22%	0.09
Boston (MA)	40,646	15.56	18%	42%	0%	57%	0%	38%	0.18
Buffalo (NY)	68,707	14.96	32%	38%	35%	50%	35%	50%	0.05
Cambridge (MA)	37,676	29.27	0%	29%	0%	28%	0%	17%	0.18
Columbus (OH)	151,591	31.23	0%	36%	26%	38%	0%	43%	0.22
Denver (CO)	298,224	31.54	0%	17%	0%	26%	0%	15%	0.16
Grand Rapids (MI)	9,764	7.44	63%	76%	59%	70%	59%	59%	0.46
Indianapolis (IN)	188,332	27.57	0%	42%	20%	33%	0%	20%	0.07
Jersey City (NJ)	9,609	11.25	54%	64%	0%	62%	0%	63%	0.07
Madison (WI)	82,156	6.14	54%	60%	61%	75%	36%	63%	0.05
Milwaukee (WI)	191,197	5.83	60%	60%	43%	67%	43%	59%	0.05
Minneapolis (MN)	171,921	11.22	29%	79%	27%	71%	0%	80%	0.11
New Haven (CT)	29,737	18.92	12%	43%	0%	36%	0%	52%	0.08
New York (NY)	652,084	15.26	25%	50%	0%	40%	0%	17%	0.07
Philadelphia (PA)	149,421	24.56	13%	32%	0%	40%	0%	39%	0.10
Pittsburgh (PA)	39,894	20.58	10%	48%	26%	26%	0%	41%	0.09

City (St.)	Trees	BioIdx (Sp)	Sp > 10%	Sp > 5%	Gen > 20%	Gen > 10%	Fam > 30%	Fam > 15%	Age dist.
Portland (OR)	248,121	–	–	–	24%	24%	0%	44%	0.12
Providence (RI)	21,892	13.13	28%	67%	25%	36%	0%	45%	0.24
Sacramento (CA)	96,941	21.91	15%	34%	0%	29%	0%	0%	0.14
San Francisco (CA)	173,166	34.16	0%	18%	0%	0%	0%	40%	0.19
San José (CA)	263,937	25.35	10%	34%	0%	10%	0%	0%	0.06
Seattle (WA)	254,576	66.43	0%	0%	20%	38%	32%	52%	0.25
St. Louis (MO)	81,537	18.29	11%	49%	24%	50%	0%	39%	0.08
Washington (DC)	192,874	38.55	0%	18%	21%	34%	0%	22%	0.21

At the neighborhood level, none of the neighborhoods in each city met the 5/10/15 rule (Tab. 5). In contrast, Denver had the most neighborhoods compliant (30), followed by San Francisco (22) and San José (20), with the 10/20/30 rule. For the optimal age distribution benchmark, San José had 35 neighborhoods that met this rule, followed by New York City (29), and Baltimore, Milwaukee, and Portland (15). These descriptive patterns reveal spatial variation in resilience capacity, as areas with lower species diversity or age-class imbalance fall below established resilience benchmarks and therefore may be more vulnerable to pest outbreaks or climate-driven mortality.

Table 5: Neighborhood-level: number of neighborhoods and the percentage of them that meet biodiversity and age benchmarks. The darker the cell highlight, the better the performance

City (St.)	Nbhds	Sp > 10%	Sp > 5%	Gen > 20%	Gen > 10%	Fam > 30%	Fam > 15%	Age breach
Ann Arbor (MI)	52	75%	100%	79%	100%	42%	100%	100%
Aurora (CO)	78	99%	99%	90%	100%	54%	100%	99%
Baltimore (MD)	276	91%	100%	78%	100%	40%	100%	95%
Boston (MA)	23	100%	100%	78%	100%	26%	100%	100%
Buffalo (NY)	35	97%	100%	91%	100%	69%	100%	97%
Cambridge (MA)	13	62%	100%	23%	100%	8%	85%	100%
Columbus (OH)	40	65%	100%	88%	100%	30%	100%	98%
Denver (CO)	78	58%	100%	31%	99%	4%	92%	100%
Grand Rapids (MI)	40	100%	100%	100%	100%	100%	100%	100%
Indianapolis (IN)	98	85%	100%	72%	100%	19%	99%	92%
Jersey City (NJ)	39	100%	100%	90%	100%	74%	100%	95%
Madison (WI)	138	99%	99%	99%	100%	84%	100%	96%

City (St.)	Nbhds	Sp > 10%	Sp > 5%	Gen > 20%	Gen > 10%	Fam > 30%	Fam > 15%	Age breach
Milwaukee (WI)	185	100%	100%	99%	100%	88%	100%	92%
Minneapolis (MN)	87	100%	100%	99%	100%	41%	100%	95%
New Haven (CT)	20	95%	100%	60%	100%	15%	100%	90%
New York (NY)	253	100%	100%	58%	100%	32%	100%	89%
Philadelphia (PA)	158	89%	100%	60%	99%	34%	99%	98%
Pittsburgh (PA)	90	99%	99%	92%	100%	57%	100%	96%
Portland (OR)	117	–	–	75%	100%	34%	100%	87%
Providence (RI)	25	100%	100%	84%	100%	44%	100%	100%
Sacramento (CA)	121	96%	100%	65%	98%	32%	94%	99%
San Francisco (CA)	114	77%	100%	32%	91%	45%	100%	96%
San José (CA)	295	93%	100%	50%	95%	26%	84%	88%
Seattle (WA)	94	38%	99%	71%	100%	63%	100%	100%
St. Louis (MO)	87	100%	100%	87%	100%	47%	100%	90%
Washington (DC)	51	29%	100%	61%	100%	12%	100%	94%

3.3 Regression Results

Among the socioeconomic predictors (Tab. 6) and control variables (Tab. 7), racial minority status and the share of households without vehicles were statistically significantly inversely associated with trends in biodiversity (Tab. 8). Suggesting that residents who identify as minorities and have limited personal vehicle mobility may be associated with lower biodiversity of street trees. Overall, socioeconomic predictors had greater explanatory power for trends in species biodiversity than in age diversity. Only the share of households without vehicles showed a positive, statistically significant correlation with trends in age diversity, suggesting that higher mobility vulnerability may be associated with a greater distance from the optimal age benchmark.

Table 6: Regression predictor variables

Numeric Predictor Variables	Valid N	Mean	SD	Min	Max
Number of Trees	5,973	575.3	657.16	1	7,854
Minority Population (%)	5,973	58.81	30.02	0	100
Population Below 150% Poverty (%)	5,973	25.25	17.29	0	100
Percentage of households with no vehicle available	5,840	30.9	24.67	0	100
Biodiversity Index (Species Level)	5,971	11.86	7.44	1	56
Age Diversity Index – Dist. to Benchmark	5,973	0.25	0.14	0	1
Number of Species Breaching Hard 5% Rule by Census Tract	5,971	5.1	1.65	0	12
Number of Species Breaching Soft 10% Rule by Census Tract	5,971	2.13	1.15	0	7
Census Tract Area in Square Miles	5,973	0.51	2.02	0	97.97

Table 7: Descriptive categorical and control variables

Categorical Variables	Sub-categories	Tract Count	%
Climate Zones	Humid Continental Hot Summers with Year-round Precipitation	4,263	71.4
	Warm Summer Mediterranean Climate	654	10.9
	Humid Subtropical Climate	631	10.6
	Cold Semi-Arid Climate	280	4.7
	Hot Summer Mediterranean Climate	145	2.4
Tree Governance Program Type	Public	4,920	82.4
	Public/Private Partnership	819	13.7
	Private	234	3.9

Table 8: Results of the regression models for equity, biodiversity, and age diversity

Predictor	Model 1a	Model 1b	Model 2a	Model 2b	Model 3a	Model 3b
Minority Population (%)	-0.010*** (0.003)	-0.00002 (0.0001)	–	–	–	–
Population < 150% Poverty (%)	–	–	-0.002 (0.005)	0.00005 (0.0001)	–	–
Households with No Vehicle (%)	–	–	–	–	-0.036*** (0.004)	0.001*** (0.0001)
Climate & Area Controls Included	Yes	Yes	Yes	Yes	Yes	Yes
Observations (n = census tracts)	5,971	5,973	5,971	5,973	5,838	5,840
Adjusted R^2	0.206	0.022	0.204	0.022	0.218	0.055

Note: Standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

3.4 Program Comparisons

Compared with private tree programs, tracts with public and quasi-public street tree programs are more likely to exhibit higher species biodiversity, providing preliminary support for our second study hypothesis (Tab. 9). However, model 4b suggests that tracts with a private program type are more likely to have a shorter distance to the optimal age benchmark than those with public or quasi-public partnerships. The low R-squared values across all age-diversity models suggest that socioeconomic and program-management types contribute little to changes in age diversity. However, these results have limitations: the dominance of public governance may reflect a broader pattern in the U.S., or it may reflect that geospatial data on trees are more readily available in cities with public governance, which could be an underlying bias in GIS-based research. Importantly, these patterns should not be interpreted as evidence of causal effects. The relationships observed here may be driven by differences in program capacity, policy frameworks, funding structures, or practitioner knowledge, rather than by program type alone. Future research should work to disentangle these potential drivers to determine whether the observed differences arise from programmatic practices, institutional conditions, or broader contextual factors that vary across urban forestry systems.

Table 9: Results of the regression models for street tree program type

Predictors	Model 4a	Model 4b
Public (Tree Program Type)	4.163*** (0.530)	0.138*** (0.012)
Public and Private Partnership (Tree Program Type)	10.812*** (0.531)	0.089*** (0.012)
Climate & Area Controls Included	Yes	Yes
Observations (census tracts)	5,971	5,973
Adjusted R2	0.299	0.048

Note: Standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

4 Conclusion

In conclusion, this research underscores the need for more consistent and comprehensive approaches to evaluating street tree biodiversity and age diversity, a need that extends well beyond the United States and reflects challenges faced by cities across the Global North and Global South. Urban tree inventories worldwide are frequently constrained by inconsistent data structures, variable monitoring practices, and limited long-term record-keeping, all of which hinder cross-city comparisons and restrict the development of evidence-based urban-forest policies. By introducing an open-source R Shiny pipeline and recommending standardized data practices, our work provides a transferable framework adaptable to diverse municipal, regional, and national contexts.

Applying this approach across 26 U.S. cities demonstrates how uneven biodiversity outcomes can emerge in various forms of urban forestry programs. These patterns echo global concerns about over-reliance on a narrow suite of species, insufficient attention to age distributions, and the concentration of environmental burdens in historically marginalized communities. They also align with global trends toward privatizing urban forests, which can reshape access to benefits and complicate equitable, resilient canopy planning. The tools and methods introduced here support planners and land managers in making strategic, data-driven decisions that avoid over-planting certain species, direct resources toward neighborhoods with biodiversity deficits, and strengthen long-term resilience to climate change and emerging pests. These insights also translate benchmark findings into actionable planting, species-selection, and neighborhood-level design decisions that strengthen long-term urban forest resilience. Taken together, the biodiversity and age-structure metrics applied in this study operationalize key components of urban forest resilience by identifying where species dominance, age imbalances, and spatial inequities may limit an urban forest's ability to withstand and recover from climate-driven disturbances. By framing these empirical patterns as indicators of resilience capacity, our results clarify how benchmarking diversity at multiple scales provides actionable guidance for strengthening urban forests' long-term adaptive potential.

By addressing foundational data limitations and leveraging open-source tools, we aim to contribute to a globally relevant urban-forest data infrastructure, one that supports more equitable, climate-resilient, and biodiverse city streetscapes, and that can be shared, compared, and continuously improved across international boundaries.

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Bridging Urban Development and Nocturnal Wildlife Conservation: A Circuit Theory-Based Ecological Corridor Network in Nanjing's Urban Core

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Abstract: Habitat fragmentation and artificial light at night (ALAN) jointly threaten nocturnal wildlife in compact cities. This study develops a framework integrating Maximum Entropy (MaxEnt) modelling, Morphological Spatial Pattern Analysis (MSPA), and circuit theory to construct nocturnal ecological networks in Nanjing's high-density urban core. We identified 21 ecological sources and 47 corridors, and located 73 pinch points, 133 barriers, and 92 break points on an ALAN-integrated resistance surface. Network vulnerabilities strongly coincide with transportation infrastructure and dense built-up zones. A hierarchical patch-corridor-matrix strategy is proposed, featuring dark-sky core zones, animal-friendly passages, and community-scale dark-night cells. This framework's practical value lies in the precise identification of ecological pinch points, barrier points and break points, providing planners with a scientific basis for improving the habitat connectivity of nocturnal wildlife in high-density urban cores through targeted, low-intervention measures, and offering operable insights for integrating dark-sky conservation into urban ecological planning.

Keywords: Nocturnal wildlife, ALAN, ecological network, circuit theory, urban biodiversity

1 Introduction

Global urbanization has caused extensive loss and fragmentation of natural habitats, producing isolated "habitat islands" across urban landscapes (HÖLKER et al. 2010). These transformations pose disproportionate threats to nocturnal wildlife, whose activity peaks overlap with human schedules and whose behaviour and physiology are highly sensitive to artificial light at night (ALAN) (MANDER et al. 2023). As key contributors to ecosystem functions, nocturnal species rely strongly on functional connectivity among habitat patches to maintain population viability (BUMGARNER & NELSON 2021). Consequently, identifying and safeguarding ecological corridors to establish functional ecological networks has become a critical task for mitigating biodiversity loss and enhancing the resilience of urban ecosystems.

Ecological network research has progressed from qualitative, expert-based approaches to quantitative simulation using GIS, remote sensing, and landscape models. Among these, cost-distance modelling approaches, such as the classic Minimum Cumulative Resistance (MCR) model, quantify landscape resistance across continuous surfaces to delineate potential corridors based on least-cost paths. In contrast, circuit theory models landscape connectivity probabilistically, analogizing species movement to electrical current flowing through a resistance network. This approach focuses on the random-walk characteristics of species, enabling the identification of critical connectivity nodes (e. g., pinch points) and areas of high movement probability, rather than a single optimal path (ZHANG et al. 2025). Although circuit theory has proven effective in conservation planning for specific taxa, its application to multi-species nocturnal ecological networks in highly urbanized environments remains limited (GUO

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et al. 2025). Moreover, ALAN is rarely incorporated as a core resistance factor in multi-species urban network modelling, resulting in an incomplete understanding of how light pollution reshapes nocturnal connectivity in high-density cities.

To address these gaps, this study focuses on Nanjing's National-level Urbanized Area in eastern China, located in the lower reaches of the Yangtze River. Characterized by high development intensity, severe light pollution, and pronounced habitat fragmentation, this area provides an ideal context for examining nocturnal ecological networks in compact cities. Focusing on nine representative nocturnal species, we integrate species occurrence data, remote sensing products, and geospatial analysis by coupling species distribution models (SDMs), morphological spatial pattern analysis (MSPA), and circuit theory. Specifically, this study aims to: (1) quantify multi-species habitat suitability and spatial patterns; (2) identify a hierarchical system of ecological sources; (3) simulate a circuit theory-based ecological corridor network; (4) locate critical pinch points and movement barriers; and (5) propose optimized network and design strategies to support dark-night-friendly ecological infrastructure planning in Nanjing.

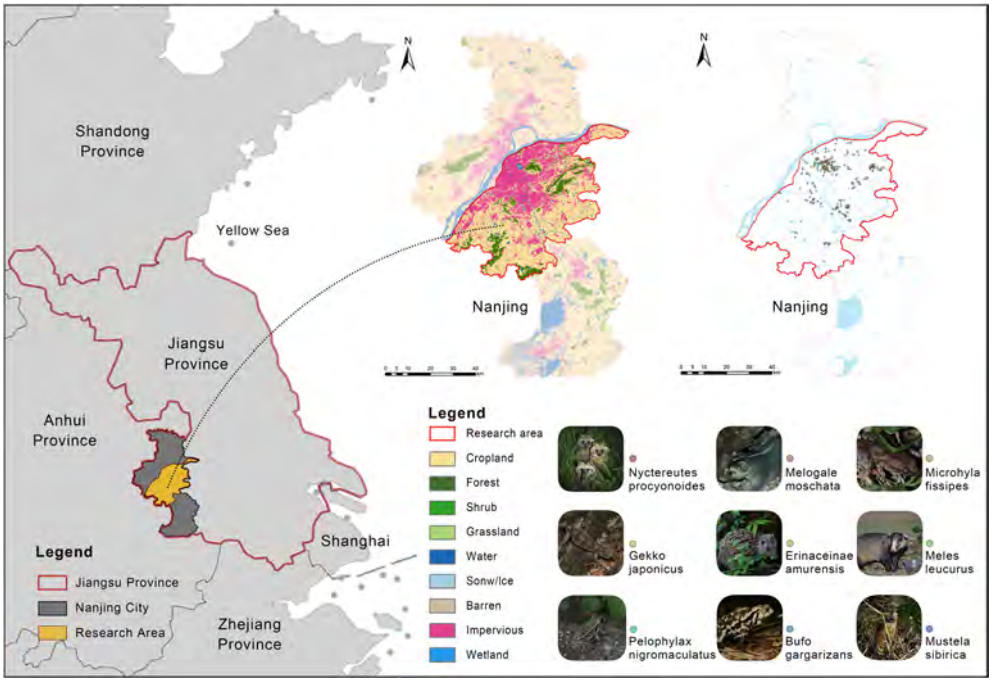

Fig. 1: Study area and spatial distribution of occurrence records for the nine nocturnal species

2 Methods

2.1 Data Acquisition and Preprocessing

Occurrence records for nine nocturnal species were obtained from the Global Biodiversity Information Facility (GBIF, a global biodiversity data network) and iNaturalist (a citizen science platform for biodiversity observations). Only research-grade records were retained, and a 1 km spatial thinning filter was applied to reduce spatial autocorrelation, resulting in 207 occurrence points (Tab. 1).

Table 1: Species scientific name, ecological functional groups and quantity

Node	Scientific name	Common Name	Ecological functional groups	Number of points
Sp1	*Nyctereutes procyonoides*	Raccoon dog	Medium-sized omnivore	8
Sp2	*Melogale moschata*	Chinese ferret-badger	Medium-sized omnivore	10
Sp3	*Microhyla fissipes*	Ornate chorus frog	Small amphibian	30
Sp4	*Gekko japonicus*	Japanese gecko	Small reptile	20
Sp5	*Erinaceinae amurensis*	Amur hedgehog	Medium-sized insectivore	20
Sp6	*Meles leucurus*	Asian badger	Medium-sized omnivore	10
Sp7	*Pelophylax nigromaculatus*	Black-spotted pond frog	Medium-sized amphibian	31
Sp8	*Bufo gargarizans*	Asiatic toad	Medium-sized amphibian	57
Sp9	*Mustela sibirica*	Siberian weasel	Small carnivore	21
Total				207

Table 2: Environmental variables used in MaxEnt model

Variable type	Abbr.	Environmental variable	Unit
Bioclimatic	Bio3	Isothermality	℃
	Bio4	Temperature Seasonality	℃
	Bio6	Minimum Temperature of the Coldest Month	℃
	Bio8	Mean temperature of wettest quarter	℃
	Bio12	Annual Precipitation	mm
	Bio14	Precipitation of the Driest Month	mm
	Bio15	Precipitation Seasonality (Coefficient of Variation)	%
	Bio16	Precipitation of the Wettest Quarter	mm
Topographic	Bio34	Slope	°
Ecological	Bio32	Land Use Type	
	Bio33	Distance to Water	
	Bio38	NDVI	
Human interference	Bio31	Nighttime Light Intensity	
	Bio36	Road Density	
	Bio37	Distance to Roads	

Environmental variables were compiled at a 30 m resolution, including: (1) 19 bioclimatic variables from WorldClim; (2) topographic variables (slope and aspect) derived from a 30 m DEM provided by the Chinese Academy of Sciences; (3) land use/land cover data from the 2020 China Land Cover Dataset (CLCD); (4) mean NDVI for 2020 derived from Landsat-8 imagery using Google Earth Engine; (5) nighttime light intensity from the 2020 Suomi NPP/VIIRS annual composite as a proxy for artificial light at night (ALAN); and (6) anthropogenic disturbance indicators, including road density, distance to roads, and distance to water bodies derived from OpenStreetMap data.

All raster layers were projected to GCS_WGS_1984 and resampled to 30 m resolution using bilinear interpolation for continuous variables and nearest-neighbour resampling for categorical data. To reduce multicollinearity in MaxEnt modelling, Pearson correlation analysis ($|r|>0.75$) was applied to 27 initial variables, yielding a final set of independent predictors (Tab. 2).

2.2 Habitat Suitability Simulation and Species Richness Analysis

Species-specific habitat suitability was modelled using Maximum Entropy (MaxEnt) 3.4.4, a widely used machine-learning algorithm for predicting species distributions based on environmental variables and species occurrence data. In simple terms, MaxEnt predicts the most suitable habitats for a species by analysing the environmental conditions where it has been observed, and it works well even with small sample sizes – common in urban wildlife research. Model features (linear, quadratic, hinge) were applied based on sample size. Models were run with 75% of data for training and 25% for testing, repeated 10 times. Performance was evaluated using AUC. Continuous suitability outputs were classified into high, medium, and low suitability classes. High-suitability areas across all species were overlaid to generate a species richness map, categorized as low (0 - 1 species), medium (2 - 4 species), and high (≥5 species) richness (ELITH et al. 2011).

2.3 Identification of Ecological Sources

Ecological sources were identified by integrating structural and functional criteria. Morphological Spatial Pattern Analysis (MSPA) is a pixel-based image processing method that characterizes the geometric and spatial connectivity of landscape patterns. It has been widely used to delineate structurally intact core areas from binary land cover maps, such as those of forests, grasslands, and water bodies. Core areas overlapping high species richness were classified as Primary Sources, while those overlapping medium richness were classified as Secondary Sources. Adjacent sources separated by low-resistance features were merged, and a minimum area threshold of 20 ha was applied to ensure ecological functionality.

2.4 Construction of Ecological Resistance Surfaces and Extraction of Corridors

A composite resistance surface was constructed to represent landscape permeability for nocturnal species movement. Seven factors – slope, land use type, distance to water, nighttime light intensity, NDVI, road density and distance to roads – were reclassified into standardized resistance values (1-9). Factor weights were determined using the Analytic Hierarchy Process (AHP) based on expert judgment, and the final resistance surface was generated through weighted overlay analysis in ArcGIS (Tab. 3).

Circuit-theory-based connectivity modelling was conducted using the Linkage Mapper toolbox (v3.0) in ArcGIS. All ecological sources were treated as focal nodes, and cumulative current flow among sources was simulated using the Circuitscape engine in "All-to-One" mode. Outputs included current density maps and corridor networks, which were hierarchically classified based on current intensity and source importance.

Table 3: Factor classification criteria and assignment

Resistance factor	Class	Resistance value	Weight
Slope	0 - 2.202	1	0.045
	2.2024 - 6.827	3	
	6.8276 - 13.214	5	
	13.214 - 20.923	7	
	20.923 - 56.162	9	
Land Use Type	Forest	1	0.201
	Grassland	3	
	Water body	5	
	Farmland	7	
	Construction land, bare land	9	
Distance to Water	0 - 271.117	1	0.051
	271.117 - 598.718	3	
	598.718 - 994.098	5	
	994.098 - 1,592.816	7	
	1,592.816 - 2,880.625	9	
Nighttime Light Intensity	0 - 10.363	1	0.313
	10.363 - 25.044	3	
	25.044 - 42.316	5	
	42.316 - 87.224	7	
	87.224 - 220.221	9	
NDVI	0.521 - 0.783	1	0.071
	0.393 - 0.521	3	
	0.266 - 0.393	5	
	0.116 - 0.266	7	
	-0.200 - 0.116	9	
Road Density	0 - 2.285	1	0.118
	2.285 - 5.331	3	
	5.331 - 9.013	5	
	9.013 - 13.710	7	
	13.710 - 32.373	9	
Distance to Roads	5,107.985 - 9,577.473	1	0.201
	3,417.843 - 5,107.985	3	
	2,028.170 - 3,417.843	5	
	901.409 - 2,028.170	7	
	0 - 901.409	9	

2.5 Identification of Pinch Points, Barrier Points and Break Points

We identified three categories of critical nodes within the ecological network based on circuit theory and spatial analysis. Pinch points are bottleneck areas within corridors where the modelled probability of wildlife movement (represented as current flow) is highly concentrated and alternative dispersal routes are scarce, making them critical for maintaining overall landscape connectivity. Barrier points refer to localized areas of exceptionally high resistance that severely impede the movement of nocturnal species, leading to degraded habitat connectivity (McRae et al. 2013). Break points are specific locations where ecological corridors are physically severed by major linear infrastructure, such as highways or railways, resulting in the direct disconnection of habitat patches.

In this study, pinch points and barrier points were identified using the Pinchpoint Mapper and Barrier Mapper modules within the Linkage Mapper toolbox, respectively. Break points were determined by spatially overlaying the simulated corridor network with a dataset of major transportation infrastructure.

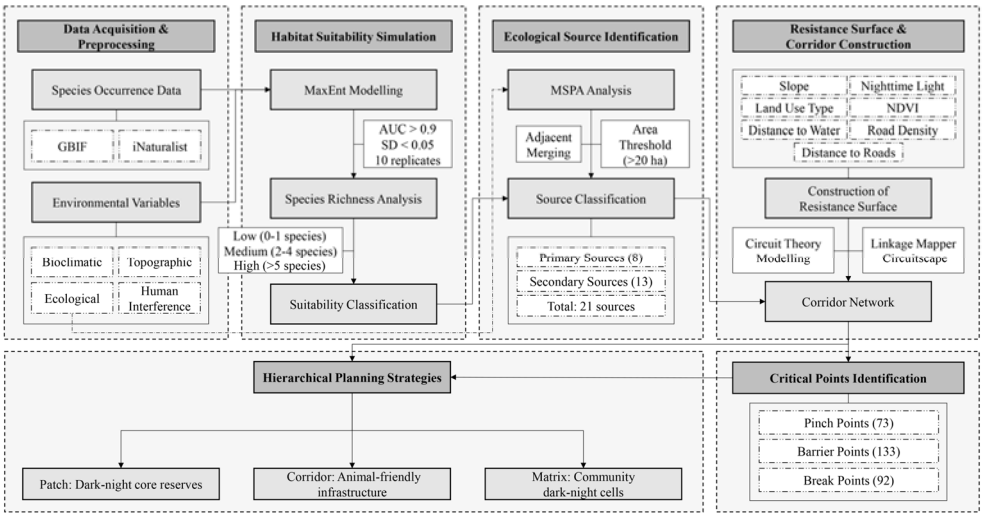

Fig. 2: Research framework

3 Results

3.1 Patterns of Habitat Suitability and Species Richness

All nine MaxEnt models showed high predictive accuracy (AUC > 0.9) and stability (SD < 0.05). Although high-suitability habitats varied among species, they consistently clustered within Nanjing's major forests, wetlands, and large urban green spaces.

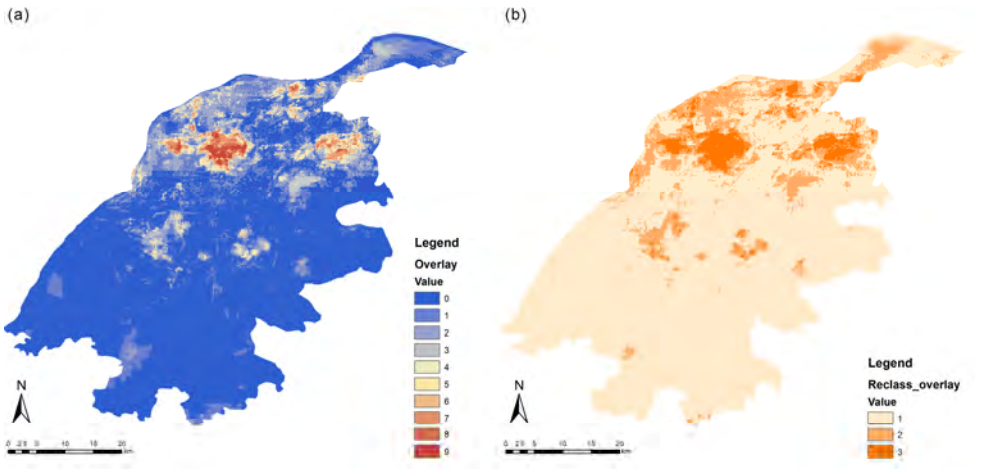

Fig. 3: Habitat suitability patterns and species richness distribution for nocturnal wildlife in Nanjing: (a) Overlay of species-specific habitat suitability maps, (b) Reclassified species richness levels

The composite species richness map revealed pronounced spatial clustering. High-richness zones (≥5 species) were primarily concentrated in the Purple Mountain-Xuanwu Lake area and the Yangtze River wetlands, identifying these areas as key hotspots for nocturnal biodiversity conservation (Fig. 3).

3.2 Spatial Distribution of Multi-level Ecological Sources

MSPA results indicate that Core areas cover 57.58 km² (28.88%), forming the structural backbone of the landscape. Bridge (14.77%) and Loop (7.22%) classes support connectivity, while Edge (14.91%) and Branch (8.83%) reflect core exposure. The high proportion of Islet patches (19.12%) indicates pronounced fragmentation.

Overlaying Core areas with species richness patterns identified 21 ecological sources, including 8 primary and 13 secondary sources. Primary sources are concentrated along the Purple Mountain-Tang Mountain-Qinglong Mountain belt, whereas secondary sources are associated with medium-sized urban green spaces, consistent with Nanjing's "mountain-water-city-forest" landscape structure (Fig. 4).

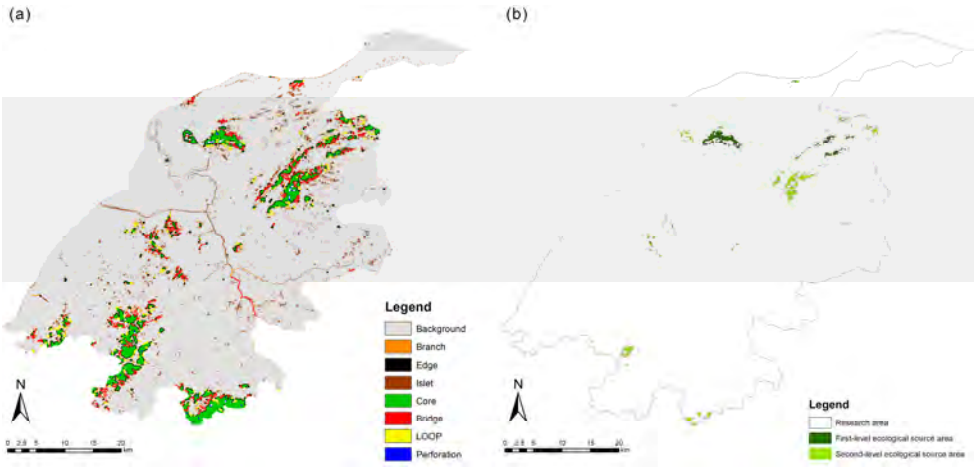

Fig. 4: Identification of ecological source areas based on MSPA and species richness patterns: (a) MSPA-derived landscape structure, (b) Overlap between core patches and high-suitability habitats

3.3 Modelling and Spatial Pattern of the Ecological Network

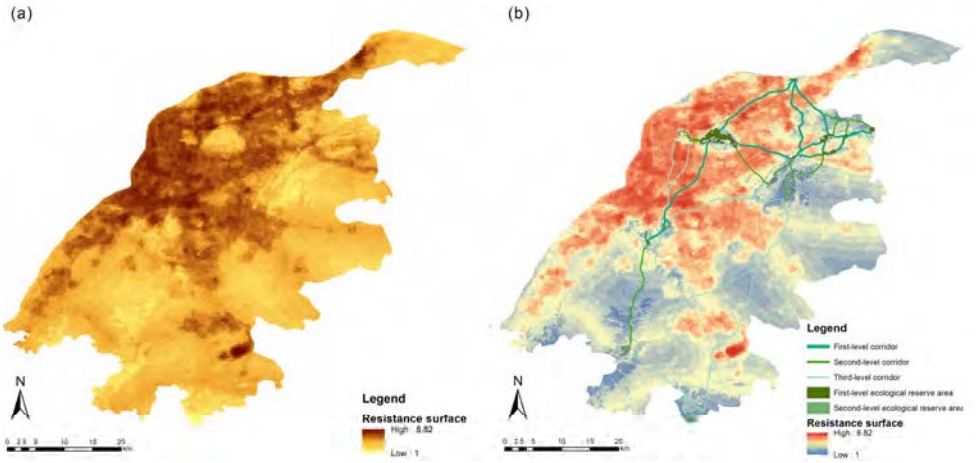

Fig. 5: Integrated ecological resistance surface and circuit theory-based ecological network: (a) Composite resistance surface, (b) Hierarchical ecological corridor network

The integrated resistance surface exhibited a pronounced radial pattern characterized by high resistance in the urban core and progressively lower resistance toward the periphery. High-resistance zones correspond to densely built-up central areas, medium-resistance zones to mixed land-use suburban areas, and low-resistance zones to peripheral suburbs and large green spaces such as Purple Mountain, which provide high-quality habitats (Fig. 5).

Circuit theory modelling identified a total of 47 ecological corridors with a combined length of 460.37 km. Corridors were hierarchically classified based on cumulative current density

and the ecological level of the connected sources. This resulted in 12 primary corridors, 14 secondary corridors, and 21 tertiary corridors. Spatially, the corridor network exhibits a "denser north, sparser south" pattern, reflecting the combined influence of complex northern topography and source concentration, as well as longer corridor spans required to traverse ecological barriers in southern areas.

3.4 Pinch Points, Barrier Points, and Break Points

A total of 73 pinch points were identified, primarily occurring at intersections between ecological corridors and major highways, rivers, and urban-rural transition zones. These locations represent critical bottlenecks for nocturnal ecological flows (Fig. 6).

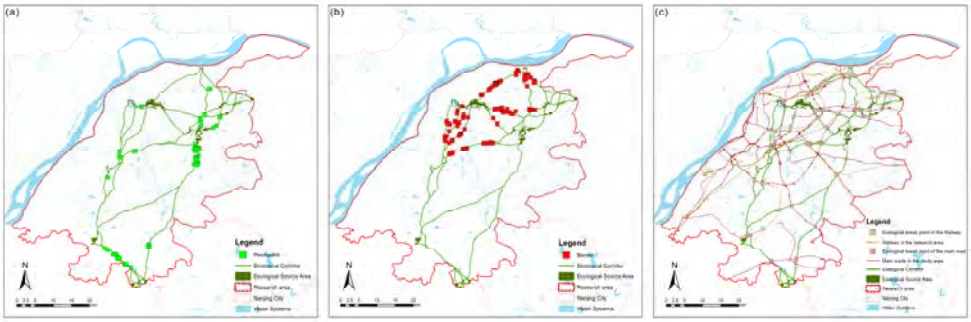

Fig. 6: Spatial distribution of pinch points (a), barrier points (b), and break points (c) in the ecological network

Additionally, 133 barrier points were detected, with a strong concentration in high-density built-up areas. This pattern reflects the cumulative effects of intensive infrastructure development and human activities, which generate a high-resistance urban matrix. Ecological restoration at these locations – such as vegetation enhancement or stepping-stone creation – would substantially improve landscape connectivity.

Furthermore, 92 break points were identified where major roads or railways physically sever ecological corridors, mainly within central and northeastern urbanized areas. Targeted mitigation measures, including wildlife overpasses or underpasses, are essential at these sites to restore network integrity.

The spatial mapping of these three types of key nodes provides a precise spatial guide for connectivity improvement: pinch points require protection to avoid further degradation of existing connectivity, barrier points need ecological restoration to reduce landscape resistance, and break points demand artificial infrastructure intervention to reconnect disconnected corridors.

4 Discussion and Conclusion

This study develops an integrated framework coupling MaxEnt, MSPA, and circuit theory, advancing urban ecological network modelling by linking species-level habitat requirements,

landscape structural patterns, and ecological process simulation within a unified workflow. Compared with conventional approaches that apply MSPA or MCR independently, the framework improves (1) ecological source identification by integrating functional habitat suitability with morphological structure, (2) connectivity representation by replacing deterministic single-path outputs with probabilistic movement networks, and (3) planning applicability by identifying spatially explicit intervention targets, including pinch points, barrier points, and break points. Such spatial precision is particularly valuable for highly fragmented urban landscapes.

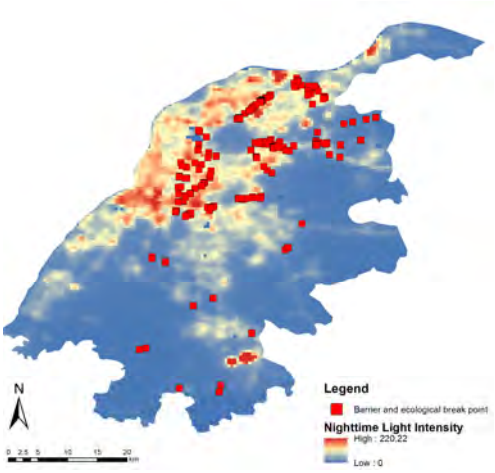

Fig. 7:
Analysis of the superposition of night light index and obstacle points

A further methodological contribution is the incorporation of ALAN as a weighted resistance factor, based on expert consultation and literature synthesis documenting the impacts of artificial light on nocturnal fauna (HÖLKER et al. 2010, SANDERS et al. 2021). By spatializing established light–ecology relationships, the model translates conceptual ecological knowledge into geographically explicit resistance surfaces, enabling the identification of areas where light pollution is most likely to constrain potential connectivity. The spatial correspondence between high light pollution and barrier concentrations should therefore be understood as a consequence of model parameterization rather than independent empirical validation. Nonetheless, the framework provides an operational basis for prioritizing "dark-night" conservation measures that can be refined as species movement data become available.

From the perspective of landscape architecture practice, the spatially explicit outputs provide a hierarchical strategic framework that bridges ecological science with design implementation across scales:

(1) At the patch scale, we propose establishing "Dark-night core reserves" featuring hierarchical lighting controls (prohibiting uplighting, enforcing colour temperature ≤3000 K) and designing topographic or vegetated edge buffers to mitigate light encroachment into sensitive areas. These core reserves are the basis of connectivity, and their protection ensures the stability of the source of nocturnal wildlife movement.
(2) At the corridor scale, addressing infrastructure-induced breakages and the "light river" phenomenon along waterfront greenways, we advocate for "Animal-friendly resilient infrastructure" (e. g., vegetated wildlife overpasses/underpasses at identified break points) and "Dark-Night-Friendly Riparian Corridors" (replacing continuous lighting

with intermittent, low-level ground fixtures while preserving segments of natural darkness). The animal-friendly infrastructure at break points and dark-night riparian corridors directly eliminate the physical and light barriers of ecological corridors, which is the key to improving the functional connectivity of the network.

(3) At the matrix scale, we promote a "Community-level dark-night cell" network. This involves establishing "lights-out" zones or periods within community green spaces, deploying motion-sensor lighting systems, and integrating ecological street furniture (e. g., insect hotels, bat boxes) with lighting design. The goal is to reconfigure the high-resistance, light-polluted urban matrix into a functional network of low-disturbance micro-refugia. These micro-refugia transform the high-resistance urban matrix into a low-resistance connectivity network, filling the connectivity gaps between large habitat patches.

These tiered strategies aim to functionally integrate the ecological security pattern with urban green space systems, blue-green networks, and slow-traffic infrastructure. By leveraging the precise identification of ecological pinch points, barrier points and break points, the strategies support the optimization of nocturnal wildlife habitat connectivity with minimal human intervention, thereby providing an actionable spatial and technical guide for achieving multi-planning integration and ecologically liveable cities.

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Impacts and Implications of Urbanization-Induced Land Use/Cover Change on Ecosystem Services: A Case Study of Zhengzhou Metropolitan Area, China

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Abstract: Accurately assessing the dynamic response of ecosystem service value to land use/land cover change is fundamental to sustainable spatial planning in areas experiencing rapid urbanization. This research analyzed the evolutionary characteristics of urbanization-induced land use/cover and ecosystem services in the core regions of Zhengzhou Metropolitan Area (ZMA), and discussed the driving mechanisms behind such modifications. Furthermore, policy recommendations were developed to support more effective environmental management strategies. The results showes that: (1) From 2000 to 2020, urban expansion came at the expense of cultivated land and ecological land in the core regions of ZMA; the key areas of urban expansion shifted from central urban to adjacent cities after 2010 directly linked with local planning policies. (2) The individual and total ecosystem service values showed a decreasing trend, and the hotspots distributed in the Songshan Mountain Range and along the Yellow River were shrinking, indicating resource pressure and ecological damage which failed to be mitigated by existing ecological policies. (3) The overall impact of urbanization rate, agricultural output value, secondary industrial output value and tertiary industrial output value on Average Ecosystem Service Value (AESV) was negative, and the agricultural output value was the most significant, with the impact degree increasing from east to west; the positive effect of population density on AESV began to manifest in 2020. This study prodivided a scientific framework to help achieve the balanced development of the social economy and ecological conservation in urban agglomerations.

Keywords: Land use/cover change, ecosystem service value, spatiotemporal dynamics, geographically weighted regression, Zhengzhou Metropolitan Area

1 Introduction

Ecosystem Services (ESs) refer to tangible products and intangible maintenance roles supplied by the natural ecosystem, are essential for human well-being (DE MOURA et al. 2024). Ecosystem Service Value (ESV) is one of the key indicators for effectively quantifying difficult-to-monetize ecosystem services, like climate regulation, carbon sequestration, and soil preservation. As the carrier of various ecosystems, efficient and reasonable land use/cover is key engine for promoting regional coordination and sustainable development (XIA et al. 2021). However, rapid industrialization and urbanization have profoundly altered the structure, function, and organization of ecosystem services through widespread land use/cover dynamics (SHI et al. 2024). Consequently, understanding the impacts and implications of urbanization-induced land use/cover change (LUCC) on ecosystem services has become an increasingly important research focus, with the aim of supporting coordinated ecological, social, and economic development.

Research on ESs originated in the mid-1960s (COSTANZA et al. 1997) and initially focused on conceptual development (DAILY & MATSON 2008), theoretical frameworks (BENNETT et

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al. 2009), as well as quantitative assessment and spatial mapping (BRYAN et al. 2018). The launch of major international initiatives, most notably the *Millennium Ecosystem Assessment* (MA) in 2001, significantly advanced this field and brought research on the coupling between urbanization-induced LUCC and ESs to the forefront of scientific inquiry (ASSESSMENT 2001). Existing research on the interactions between ESs and LUCC mainly has two aspects: (1) constructing suitable indicators reflecting land use/land cover changes, such as urbanization rate, land use dynamic index, landscape metrics, and ecological contribution rate, to evaluate the effects of changing land use/land cover on the environment (BENNETT et al. 2009, CHUANGLIN 2018); (2) applying quantitative approaches (e. g., correlation analysis, regression models) to demonstrate that rapid land use/land cover changes have negative impacts on ESs in urbanizing areas (FABER & VAN WENSEM 2012, ZHU et al. 2020). Despite these advances, integrated research combining qualitative assessments of policy effectiveness with quantitative analyses of socioeconomic drivers of ESV change remains limited. Such integrative approaches are essential for informing decision-makers and guiding the design of interventions that enhance positive outcomes while mitigating negative ecological impacts.

The ZMA, with Zhengzhou as its core city, extends outward and drives regional development across eight surrounding cities, emerging as one of the fastest-growing and most economically dynamic urban agglomerations in central China. The study period (2000-2020) covers twenty years of profound socio-economic transition in the Zhengzhou Metropolitan Area, LUCC posed substantial threats to regional ESs throughout the period of rapid industrialization and urbanization. Without intensified attention and effective management, ecological and environmental issues are likely to become a major bottleneck to the sustainable development of the ZMA. Accordingly, this study selects the core areas of the ZMA – Zhengzhou, Kaifeng, and Xuchang – as empirical case regions, in line with relevant planning frameworks and previous research findings. The objectives of this study are to:

(1) examine the urbanization-induced spatiotemporal evolution of land use/cover pattern and the corresponding ESV responses in the core regions of ZMA;
(2) relate these changes to planning and ecological policies implemented at different governance levels as well as socioeconomic trends over the past two decades;
(3) explore pathways for optimizing future policy-making to support sustainable urban development.

2 Materials and Methods

2.1 Study Area

The core regions of the Zhengzhou Metropolitan Area encompass Zhengzhou, Kaifeng, and Xuchang in the hinterland of Henan Province (33°43′N-35°12′N, 112°43′E-115°16′E). The climate in this region belongs to the warm temperate continental monsoon climate, with mean annual temperatures of 12-16°C and precipitation of 586-668 mm. The elevation increases from the east to the west, and the Yellow River delineates the northern boundaries of Zhengzhou and Kaifeng. As the political, economic, and cultural centers of Henan Province, the ZMA occupies 11.3% of the province's land area while supporting nearly 20% of its population and generating over 30% of its GDP (ZHANG et al. 2021). The location map of the study area is presented in Figure 1.

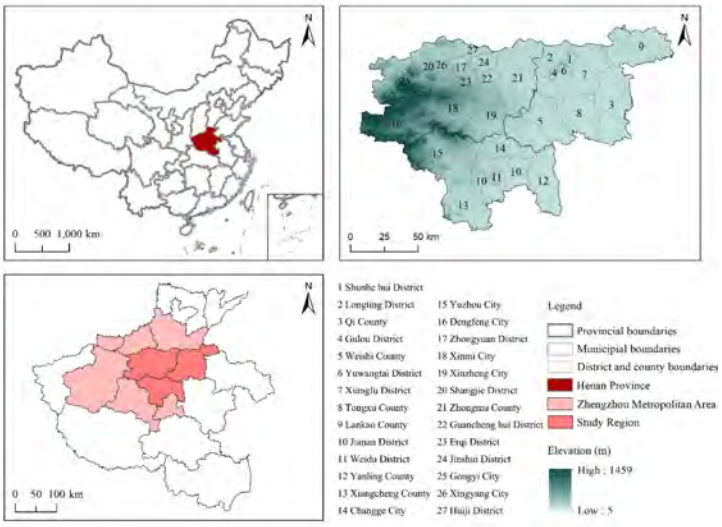

Fig. 1: Geographical location of the core regions of ZMA

2.2 Data Sources

To support the analysis of land-use change and ecosystem service dynamics, multiple spatial and socioeconomic datasets were collected and integrated. First, land-use/cover data with a spatial resolution of 30 m × 30 m for the period 2000-2020 were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (RESDC, http://www.resdc.cn/). These data were used to calculate LUCC and ESV. Second, a digital elevation model (DEM) with a spatial resolution of 30 m × 30 m was acquired from the Geospatial Data Cloud (http://www.gscloud.cn/). Third, population density data at a 1 km raster resolution were downloaded from WorldPop (https://www.worldpop.org/). Finally, socioeconomic data – including grain yield, grain sown area, urbanization rate, gross agricultural output value, and gross output values of secondary and tertiary industries – were collected from the statistical yearbooks of Zhengzhou, Kaifeng, and Xuchang cities for the period 2000-2020. Grain price data were obtained from the China Farm Product Cost-Benefit Survey (http://cnki.nbsti.net/).

2.3 Methods

To quantify land use/cover change and evaluate its impacts on ecosystem services, this study employed the following analytical methods:

(1) Land Use Transfer Matrix for Accessing LUCC

The land-use transfer matrix is an analytical method used to characterize the direction and magnitude of conversions among different land-use and land-cover types over a specified period. This approach effectively captures the structural changes in land-use composition before and after transitions within a given region, providing clear insights into dominant conversion pathways and transformation patterns (WANG et al. 2022).

(2) Equivalent Factor Method for Calculating ESV

This study adopts the ESV assessment framework originally proposed by Costanza et al. Building on this framework, Xie et al. conducted a large-scale expert survey involving more than 700 Chinese ecologists and developed a classification system for ESs as well as the equivalent value factor method tailored to the Chinese context (XIE et al., 2008). Generally, the economic value of one standard equivalent factor is equal to 1/7 of the market value of the average grain yield per unit area in the current year (CHEN et al., 2012). The standard equivalent factor was subsequently calculated based on the average net economic value of three major staple crops (wheat, corn, and soybean), and was estimated at 321.76 USD ha^{-1} $year^{-1}$ (XIE et al., 2015). Based on these equivalent factors, ESV per unit area for different land-use types were derived and summarized in Table 1. The ESV was calculated using the following formulas:

$$E_a = 1/7 \sum_{i=1}^{n} \frac{q_i p_i}{M} \quad (1)$$

$$E_{ck} = E_a \times V_{ck} \quad (2)$$

$$ESV = \sum_{k=1}^{n} \sum_{c=1}^{m} A_k \times E_{ck} \quad (3)$$

where ESV indicates the total value of ecological services (USD); E_a indicates the economic value of food production service per unit area of farmland; p_i and q_i indicate the average price (USD/kg) and the total yield (kg) of the grain type i, respectively; and M indicates the total sowing area of all grains (hm^2); V_{ck} indicates equivalent value factor per unit area of the ecological services of land use/cover type k; n is the number of land -use types; and A_k indicates total area of the specific land use/cover type k (hm^2).

Table 1: Table of equivalent coefficients for ESV per unit area (USD ha^{-1} $year^{-1}$)

Primary types	Secondary type	Farmland	Forestland	Grassland	Water body	Barren land
Provisioning services	Food production	380.15	129.70	169.95	292.94	0.00
	Raw material	178.90	295.18	250.45	163.24	0.00
	Water supply	8.95	152.06	138.64	2432.98	0.00
Regulating services	Gas regulation	299.65	970.51	881.06	597.07	8.95
	Climate regulation	161.01	2907.05	2330.12	1317.12	0.00
	Purify regulation	44.72	863.17	769.25	2046.12	44.72
	Water regulation	120.75	2119.91	1708.45	28281.17	13.42
Supporting services	Soil regulation	460.66	1185.18	1073.37	724.53	8.95
	Nutrient cycling	53.67	89.45	80.50	55.90	0.00
	Biodiversity	58.14	1077.85	974.98	2330.12	8.95
Cultural services	Aesthetic landscape	26.83	474.07	429.35	1480.36	4.47

(3) Geographically Weighted Regression Model for Identifying the Drivers of ESV

The Geographically Weighted Regression model estimates the local regression on adjacent individuals of each group through geographic coordinates and core function, with the advantage that each sample point has a unique regression coefficient value (ZHU et al., 2020). Thus, for spatial data where non-stationarity exists, the strength of influence and spatial heterogeneity of explanatory variables at multiple scales can be better captured with the following regression model:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{n} \beta_j(u_i, v_i) x_{ij} + \varepsilon_i \quad (4)$$

where y_i indicates the dependent variable at sampling point i; (u_i, v_i) indicates the spatial coordinates at sampling point i; x_{ij} indicates jth independent variable at sampling point i; β_j indicates the jth regression parameter at sampling point i; ε_i indicates the random error term.

Based on existing research results, we selected easily accessible and quantifiable indicators in terms of population, economic development and industrial structure. Before modelling, the Variance Inflation Factor (VIF) was applied to test for multicollinearity among the five indicators. The AESV of 2000, 2010 and 2020 were used as the objects of analysis to explore the dominant factors of spatial heterogeneity of ESV in the core regions of ZMA. The test results showed that the VIF values of each driver were <10 (Table 2) and all passed the multiple linearity test.

Table 2: Results of multiple collinear diagnoses

Year	Population density	Urbanization rate	Agricultural output value	Secondary industrial output value	Tertiary industrial output value
2000	2.621	5.208	3.027	5.623	4.858
2010	6.923	8.905	3.974	1.569	2.543
2020	4.142	3.001	3.824	2.674	2.313

3 Results

3.1 Temporal and Spatial Variation of Land Use/Cover

From 2000 to 2020, the core regions of the ZMA experienced a substantial expansion of urban space, largely at the expense of agricultural land and green spaces (Fig. 2). Urban construction land expanded primarily through edge expansion and compact infilling in the central urban areas of Zhengzhou, Kaifeng, and Xuchang, while linear and leapfrog development patterns were more prevalent in the surrounding regions. After 2010, the focus of urban expansion gradually shifted toward adjacent cities and districts, including Zhongmu, Xinzheng, Changge, and Longting District. Over the same period, the core regions of ZMA underwent substantial land-use transitions, with 41.40% (9816.98 km²) of the total area experiencing land-cover conversion (Figure 3). Farmland suffered the greatest loss (2,611.44 km²), primarily being replaced by construction land (2,398.14 km²) for urban and rural expansion. Conversely, farmland became the primary recipient of other land types, absorbing over 50% of the decreased areas of forest, grassland, water, and barren land. The interconversion be-

tween forestland and cropland, as well as grassland and cropland, was concentrated in the mountain-plain ecotones due to agricultural reclamation, while the shrinkage of water bodies was most pronounced along the lower reaches of the Yellow River.

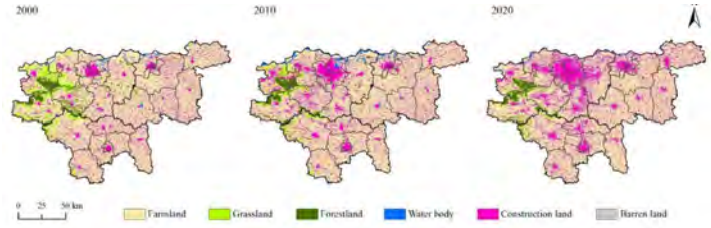

Fig. 2: Spatial distribution of land use/cover from 2000 to 2020

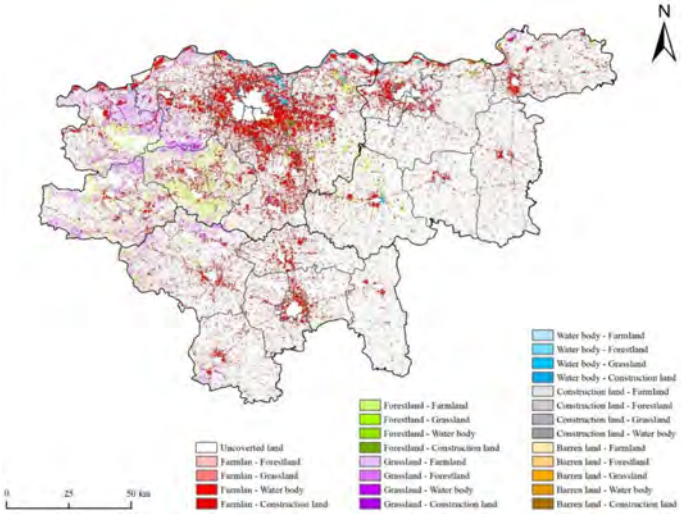

Fig. 3: Land use transfer map of the core regions of ZMA during the period 2000-2020

3.2 Temporal and Spatial Variation of ESV

Dramatic changes in ESV were evident for individual ecological functions and each land use/cover type, as demonstrated by Figure 4, Table 3, and Table 4. Water regulation and soil regulation were the dominant ecosystem service function categories, followed by climate regulation, food production and gas regulation. It was observed that the ESV of water bodies increased by 4.69 million USD in the earlier period (2000-2010), which greatly compensated for the loss of ESV of farmland, forestland and grassland. In the later period (2010-2020), although the ESV of farmland and forestland had less reduction compared to the earlier period (2000-2010), the negative trend in the ESV of water bodies was as high as 117.6 million USD, indicating that the increase or decline in the area of water bodies affected the change in the total value of ESs directly.

Coldspots/hotspots exhibited remarkable cluster features in the core regions of ZMA (Figure 5). Hotspots had continued to shrink over the past 20 years due to the overexploitation of

tourism resources, which had made the Yellow River Basin and the Songshan Mountain ecologically sensitive and fragile areas. While coldspots further increased with the expansion of construction land and the degradation of ecological functions in central urban.

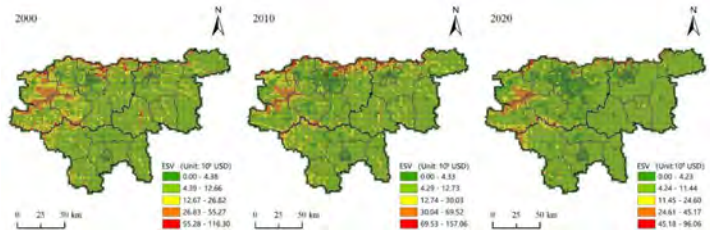

Fig. 4: Spatial distribution of ESV at the grid scale in the core regions of ZMA from 2000 to 2020

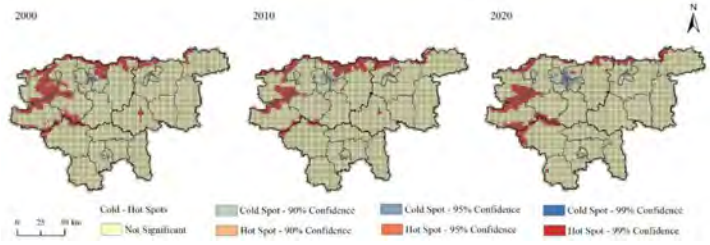

Fig. 5: Spatial distribution of ESV cold/hot spots at the grid scale

Table 3: Individual ESV and ESV change ratio in the core regions of ZMA

Primary type	Secondary type	ESV（10^8 USD）			ESV change ratio（%）		
		2000	2010	2020	2000-2010	2010-2020	2000-2020
Provisioning services	Food production	5.73	5.47	5.23	-1.88	-4.49	-8.73
	Raw material	3.07	2.84	2.65	-7.49	-6.69	-13.68
	Water supply	1.21	1.41	0.63	16.53	-55.32	-47.93
Regulating services	Gas regulation	6.08	5.50	4.87	-9.54	-11.45	-19.90
	Climate regulation	7.39	6.09	4.65	-17.60	-23.65	-38.08
	Purify regulation	2.78	2.57	1.62	-7.55	-36.96	-41.73
	Water regulation	14.70	16.97	7.83	15.44	-53.86	-46.73
Supporting services	Soil regulation	8.75	7.99	7.21	-8.69	-9.76	-17.60
	Nutrient cycling	0.93	0.86	0.80	-7.53	-7.50	-13.98
	Biodiversity	3.44	3.14	2.02	-8.72	-35.67	-41.28
Cultural services	Aesthetic landscape	1.68	1.61	0.98	-4.17	-39.13	-41.67

Table 4: ESV for each land use type

Year	Item (10^8 USD)	Farmland	Forestland	Grassland	Water body	Barren land
2000	ESV	25.29	9.56	7.45	13.45	0.01
2010	ESV	24.30	7.13	4.88	18.14	0.00
2020	ESV	23.90	6.71	1.48	6.38	0.00
2000-2010	Value change	-0.99	-2.43	-2.57	4.69	-0.01
2010-2020	Value change	-0.40	-0.42	-3.40	-11.76	0.00
2000-2020	Value change	-1.39	-2.85	-5.97	-7.07	-0.01

3.3 Socioeconomic Driving Factors of AESV

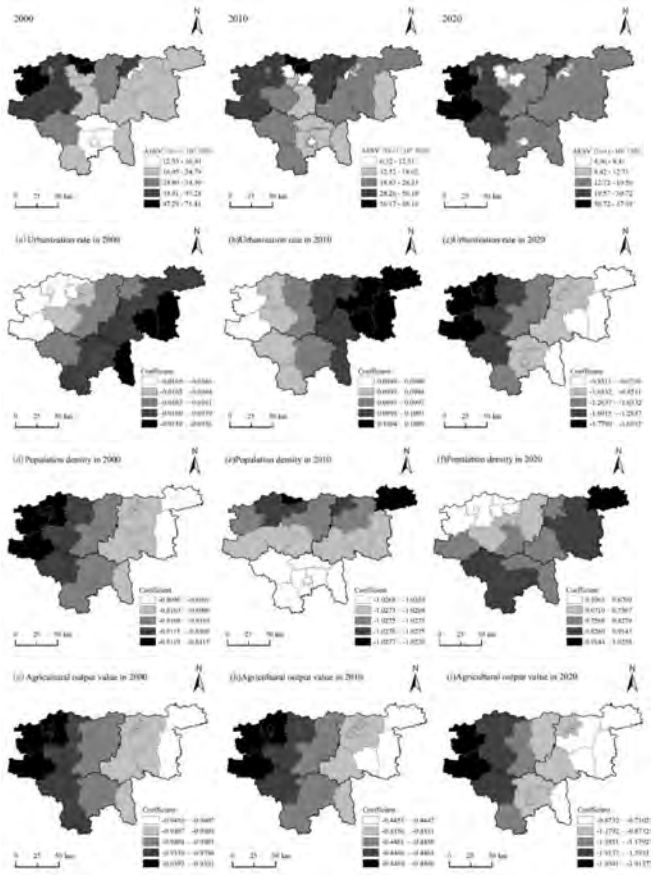

Fig. 6 Spatial distribution of AESVs at the county (district) scale in the core regions of ZMA

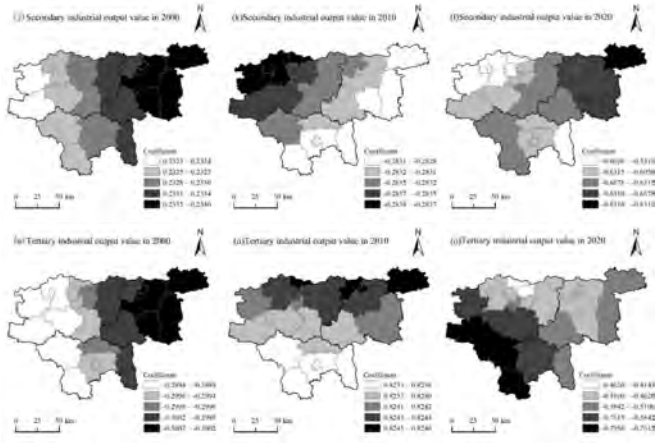

Fig. 7: Spatial distribution of driving factors regression coefficients

The overall effect of urbanization rate on AESV in the core regions of ZMA was negative but showed a lower intensity of positive impact in 2010 (Figure 6). The influence of population density on AESV shifted from negative to positive over the study period. In 2000 and 2010, negative impacts were more pronounced in western and northern regions compared to eastern and southern areas (Figure 7). Differences in industrial structure played an important role in shaping the spatial differentiation of AESV in the core regions of ZMA. Agricultural output value had a negative impact on AESV, with the magnitude increasing from east to west. Secondary industrial output value shifted from positive to negative influence on AESV, with heavily industrialized areas (e. g., Huiji, Zhongyuan Districts, and Xingyang City) experiencing significant negative effects. Tertiary industrial output value had an overall negative impact on AESV, except in areas with advanced service sectors such as Longting and Gulou Districts.

4 Optimization Suggestions

4.1 Strengthening Rigid Constraints on Ecological and Agricultural Land Protections

Guided by the principles of ecological priority and sustainable development, regulatory frameworks must be optimized to safeguard high-contribution but environmentally sensitive biotypes, including woodlands, grasslands, and aquatic systems. The fundamental status of farmland must be strictly upheld through the rigorous enforcement of the Land Administration Law of the People's Republic of China. Beyond preservation, strengthening agricultural infrastructure is essential to enhance land productivity and soil quality. Furthermore, explicit spatial boundaries for infrastructure development (e. g., transportation and residential construction) must be established to prevent urban encroachment on designated ecological reserves. By combining pollution prevention with targeted ecological restoration, land-use structures should be dynamically managed according to local conditions, thereby continuously enhancing ESV.

4.2 Implementing Zoning-based Management and Ecological Restoration

In accordance with China's Major Function-Oriented Zoning strategy, priority protection should be afforded to key ecological source areas – such as Mount Song and the Yellow River – that deliver essential life-support services and harbor high levels of biodiversity. This protection should be implemented through the establishment of ecological buffer zones to reduce anthropogenic pressures. At the same time, in high-density and ecologically vulnerable central urban areas, planning strategies should emphasize the integration of green ecological infrastructure to enhance urban resilience. In the peri-urban fringes of the Zhengzhou Metropolitan Area, which function as critical agricultural production zones for Henan Province, targeted investments in agronomic technologies and capacity-building are necessary to ensure a stable and secure regional food supply.

4.3 Advancing Regional Coordination and Fine-grained Governance

To achieve balanced regional development, a coordinated mechanism at the county and district levels is required to coordinate industrial restructuring with infrastructure expansion. From a methodological perspective, government planning should integrate quantitative analyses of LULC dynamics with long-term ESV monitoring. Implementing management at the grid scale is particularly advantageous, as it enables the alignment of ecological units with administrative township boundaries, providing a robust framework for spatial planning and regulation. Such an approach facilitates the translation of macro-level policy objectives into street- and village-level indicators, ensuring a shift from broad spatial strategies to fine-grained, actionable governance.

5 Conclusion and Outlook

This paper characterized rapid urbanization-induced spatiotemporal dynamics of land use/cover and ESV using remote sensing data and quantitative methods, highlighting the relationships among LUCC, ESV changes, and socioeconomic driving factors in the ZMA core regions from 2000 to 2020. The main conclusions are as follows.

(1) Rapid urbanization came at the expense of agricultural land, water bodies and green space, which have been replaced by clustered construction land. Spatially, due to the development of major projects including the Zhengzhou-Kaifeng New Urban District, Xinzheng Comprehensive Free Trade Zone, and Zhengzhou Airport Comprehensive Economic Zone during the second decade (2010-2020), urban expansion progressively extended from central cities to peripheral counties/cities including Zhongmu, Xinzheng, and Xinmi.

(2) Over the past two decades, total ESV continuously declined. High-value zones, primarily distributed in the Song Mountains and along the Yellow River, contracted significantly, while low-value zones in the three central cities expanded correspondingly. Losses in 11 individual ESs were more severe during the second decade (2010-2020), indicating that existing conservation measures were insufficient in protecting high-ESV land types, particularly water bodies, forests, and grasslands.

(3) Agricultural output value had the strongest negative impact on AESV, with its influence magnitude increasing from east to west. Urbanization rate and tertiary industry output value showed temporary positive effects on AESV in 2010, while the spatial pattern of negative

impacts shifted from the west (2000) to the east (2020). As urbanization matured, population density effects on AESV transitioned from negative to positive, while secondary industry effects exhibited an opposite trend.

To ensure the long-term sustainable management of land-use and land-cover systems and the continued provision of ESs in the core regions of the Zhengzhou Metropolitan Area (ZMA), greater emphasis should be placed on optimizing land-use structure and safeguarding key ecological source areas. Furthermore, long-term, multi-scale monitoring is essential for enabling differentiated and refined planning and management strategies. Overall, this study provides both a theoretical foundation and a practical framework for enhancing ESs under conditions of urbanization-induced land use/cover change.

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Research on a Multiscale Urban Ecological Network Integration Method Based on Network Analysis: A Case Study of Hegang City

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Abstract: The ecological survival of resource-extractive cities like Hegang hinges on how effectively their green infrastructure connects across fragmented urban and regional landscapes. Moving beyond traditional single-scale assessments, this research integrates established GIS and network analysis protocols to diagnose the multiscale connectivity of Hegang's ecological network. By identifying 40 regional and 10 urban-scale sources, we built a comprehensive resistance framework that accounts for both mining-induced disturbances and urban expansion. Our findings reveal a precarious structural dependency: the entire cross-scale system relies heavily on a single "backbone" path, creating a bottleneck for ecological flows. Specifically, Node 2 in the western sector emerged as a vital node with high degree centrality, functioning as a primary gateway for regional biodiversity into the city center. Rather than seeking purely theoretical novelty, this study translates these topological insights into a three-tiered planning strategy – strengthening cores, adding paths, and cultivating nodes – offering a concrete spatial blueprint for planners to prioritize restoration efforts in declining industrial regions.

Keywords: Ecological networks, cross-scale connectivity, node degree centrality, Hegang City

1 Introduction

With the deepening of urbanization, the continuous expansion of built-up areas has resulted in increasingly severe ecological fragmentation and functional degradation (SERRET et al. 2014, YU et al. 2016). As a natural solution for maintaining biodiversity and ensuring ecological security, ecological networks have therefore become a core research focus in landscape ecology and urban planning (WANG et al. 2019A). Their theoretical evolution has shifted from early "patch-path-matrix" models toward the synergistic optimization of both ecological structure and process at multiple spatial scales (FU et al. 2025).

Ecological network research focuses predominantly on two key scales: the regional scale (e.g., city-region, metropolitan area), which emphasizes biodiversity, ecosystem integrity, and large-scale processes such as species migration. The urban scale, which addresses services directly benefiting residents, including recreation, microclimate regulation, and environmental quality (NING 2021). However, mechanisms that effectively link these scales remain lacking, weakening the integration of macro-scale ecological flows into the urban core and limiting the feedback of internal urban ecological needs into regional planning(WANG et al. 2019B, ZHONG et al. 2014). As a result, both the structure and function of ecological networks are fragmented. Addressing this gap by developing systematic multi-scale integration, identifying bridging nodes, and proposing spatial optimization strategies is now a central scientific challenge.

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The construction of ecological networks generally adopts the workflow: ecological source identification-resistance surface construction extraction. Among these, the Morphological Spatial Pattern Analysis (MSPA) method has significantly strengthened the scientific basis for source identification (CIMON-MORIN & POULIN 2018). Ecological paths are commonly generated using the Minimum Cumulative Resistance (MCR) model, whose reliability depends strongly on the rational weighting of resistance factors such as land use, slope, and road proximity (CUI et al. 2020). Although graph theory provides a robust framework for evaluating ecological networks, its advanced theories and diagnostic indicators remain underutilized, resulting in analyses that seldom move beyond basic topological description. Most studies use only fundamental indicators, such as the connectivity index and path density, for analysis (ZHU et al. 2020). We argue that the true utility of node degree centrality and Minimum Spanning Tree (MST) analysis lies in their ability to diagnose systemic vulnerabilities – yet these metrics are frequently relegated to basic descriptions rather than actionable insights.

This study addresses this practical need. Using Hegang City – a landscape profoundly altered by long-term coal mining – as a laboratory, we provide an integrated application of existing GIS and graph theory procedures to solve real-world connectivity problems. By characterizing "bridging nodes" through a systematic overlay of municipal and urban data, we move past the "executive summary" style of reporting toward a diagnostic logic that identifies where restoration is most urgent. Our goal is to demonstrate how these established technical procedures can be synthesized into a coherent strategy for ecological resilience in transitioning resource-based cities.

2 Methods

2.1 Research Area and Data Sources

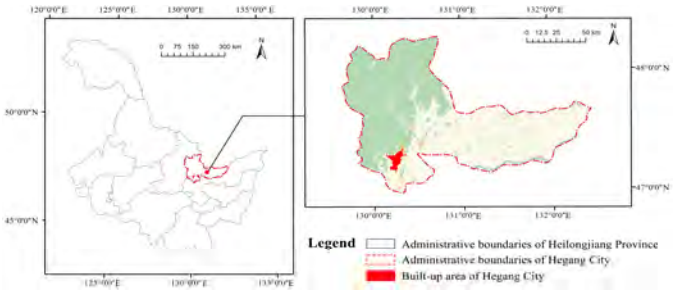

Fig. 1: Research area

Hegang City in Heilongjiang Province is a resource-based city with a high level of urbanization. It has undergone distinct developmental phases – coal-driven prosperity, resource depletion, and ongoing economic transformation – and currently faces significant challenges, including population decline and economic structural imbalance. Despite its ecological endowment from the surrounding Xiaoxing'anling forest, prolonged coal mining activities have caused severe geological disturbances and landscape fragmentation (ZHANG et al. 2022). In this context, its strategic shift toward "ecological city construction" offers a representative model for studying sustainable development pathways in resource-dependent cities. This

study uses 2024 30-meter-resolution raster data, incorporating land-use, topographic, and socioeconomic indicators to build the network.

2.2 Ecological Source Identification

MSPA was used to classify landscape elements into core areas, islands, and edges. Among them, core areas can provide sufficient habitats for species and ensure biodiversity (Yu et al. 2016). At the regional level, "Core areas" of large natural habitats (≥ 0.5 km²) were extracted. These were further screened using the Patch Connectivity (PC) index to ensure strong ecological functionality (MITCHELL et al. 2013). While at the urban level, we focused on the vital parks and green spaces within the built-up area.

2.3 Construction of the Comprehensive Resistance Surface

The resistance surface is the core carrier that reflects the difficulty of spatial movement for ecological processes. To accurately construct a comprehensive resistance surface that can represent the ecological security pattern of Hegang City, this study, based on traditional construction factors, supplements them with factors reflecting the intensity of human activities (nighttime light data and per capita GDP). At the same time, in the construction of the resistance surface in the built-up area, a natural attraction factor (the distribution of street trees) is also included. All selected factors are classified and standardized to eliminate the influence of different dimensions; the weights of each factor are determined using the Analytic Hierarchy Process (AHP) expert scoring method, and the comprehensive resistance surface is ultimately constructed in ArcGIS.

2.4 Building the Integrated Network

The potential ecological paths are extracted using the minimum cumulative resistance (MCR) model (YU et al. 2022). The Linkage Mapper toolbox is used to generate minimum-cost paths connecting the various source areas, which serve as potential paths.

1) Construction of basic ecological network: Classify the resistance values of potential paths at both the regional and built-up area scales. Select the paths with connectivity in the top 30% as critical ecological paths to construct the ecological network at both scales.

2) Cross-scale connection network extraction: Extract the municipal sub-networks associated with the built-up area, and perform spatial overlay with the built-up area network to identify the cross-scale correlation parts.

3) Identification of cross-scale backbone paths: Connectivity is both the core fundamental characteristic and one of the most critical functions of ecological paths. Therefore, based on the premise of connectivity between source points, this paper extracts the Minimum Spanning Tree (MST) of the ecological network as the backbone path (NEWMAN, M. E. J. 2010). This is obtained using the Kruskal algorithm.

To turn this topology into a planning tool, we calculated the degree centrality of nodes where regional and urban paths intersect. Finally, using the Natural Breaks method, we clustered these nodes into five distinct priority levels. This statistical grouping allows planners to dis-

tinguish “Critical” nodes from “Marginal” ones, transforming abstract graph theory into a clear hierarchy for land-use zoning and habitat reinforcement.

3 Results

3.1 Distributional Result of Ecological Sources

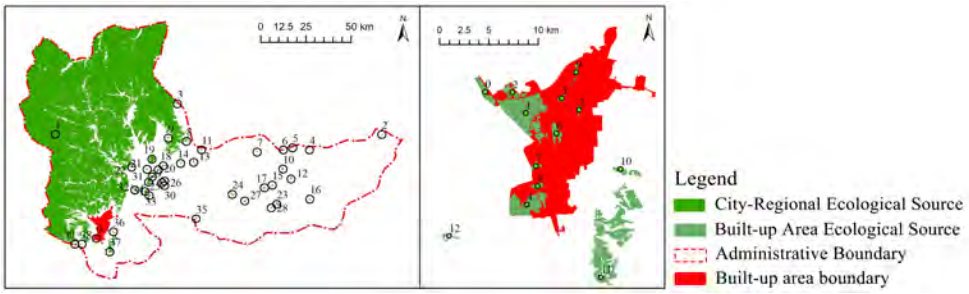

Fig. 2: Identification results of ecological sources

The geometric and functional evaluation of landscape elements identified 40 distinct ecological sources across the municipal territory. Spatially, these sources exhibit a stark “west-dense, east-sparse” configuration. The expansive natural habitats (totalling 5,921.3 km²) fringing the Xiao Xing'an Mountains in the west serve as the structural anchor for regional ecological security. In contrast, the 10 sources identified within the built-up area are smaller and more fragmented. This pattern – where high-energy regional sources envelop isolated urban patches – indicates that urban ecological functions are fundamentally subsidized by energy flows from the surrounding macro-landscape.

3.2 Resistance Surfaces and Ecological Paths

The comprehensive resistance analysis highlights that anthropogenic interference, measured by nighttime light and GDP intensity, remains the primary barrier to ecological movement. Out of an initial pool of 780 municipal paths, our screening process retained only 178 high-connectivity corridors to form the regional skeleton. Within the urban core, although 145 potential paths were generated, only 46 survived the low-resistance threshold. This drastic reduction reflects how urban sprawl has eroded natural conduits, leaving the internal network in a state of high structural fragility.

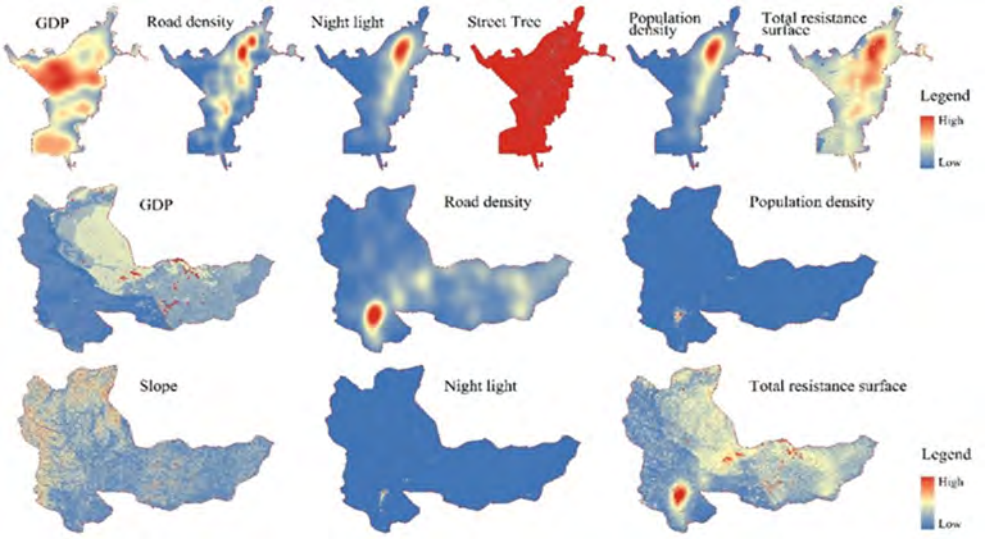

Fig. 3: The comprehensive resistance surface

3.3 Result of the Current Cross-Scale Connectivity

Further analysis revealed that within the municipal ecological network, a sub-network consisting of 10 nodes and 17 edges surrounds the built-up area. Moreover, this sub-network plays a crucial supporting role in the cross-scale connections of the ecological networks at both levels. Therefore, this study has isolated this sub-ecological network (with 15 edges) for analysis. The remaining parts make relatively weaker contributions to cross-scale connections and are thus not included in the following analysis.

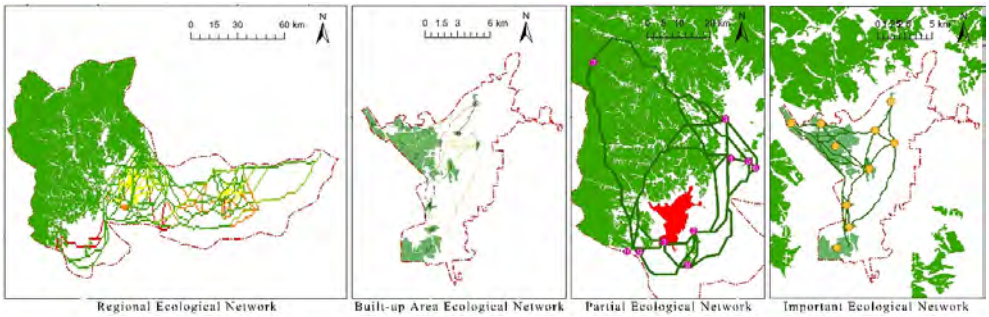

Fig. 4: The municipal ecological network

To clarify the key characteristics of the core elements of cross-scale connections in Hegang City, this study simplifies the ecological source areas and potential paths into a “node-edge” topological structure. It calculates the edge betweenness of 61 connection edges, and ultimately identifies 18 backbone paths and 7 newly formed nodes (Figure 5). Subsequently, the

newly formed nodes are combined with the ecological source points, and the node degree centrality is calculated (Figure 5). Moreover, using the natural discontinuity classification method of "minimum within-group difference and maximum between-group difference", it is divided into five levels (Figure 6).

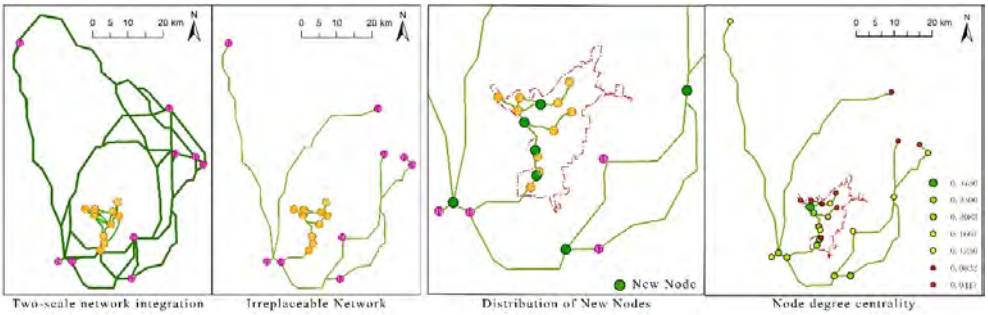

Fig. 5: The current cross-scale ecological network

The analysis of node degree centrality indicates that the most critical node is located on the west side of the built-up area (Node 2). Nodes with higher levels and higher degree centrality also mainly concentrate on the west side of the built-up area. Nodes with low degree centrality are mainly distributed at the network endpoints, and their connections with other nodes are weak, resulting in poor connectivity. Overall, the cross-scale connection paths with higher importance run north-south throughout the built-up area. Among them, the connection between nodes 5 and 18 in the southwest is a critical ecological node, and the backbone path connecting them serves as the primary cross-scale connection in the current situation.

3.4 Optimization of Cross-Scale Connectivity

Based on the diagnostic synthesis of topology and resistance, we propose a hierarchical intervention strategy (Figure 6):

1) The only cross-scale connecting backbone path between the two-tier ecological networks (2-5 path) needs to strengthen ecological restoration and protection efforts. Ensure that the ecological functions of the key structural nodes remain stable, prevent loss of ecological functions due to human construction interference, and prevent damage to the only connecting backbone path in the current situation.

2) There are three parallel backbone paths in the built-up area and the municipal area network, providing potential space for improving the connectivity between the networks. Among them, the 7th and 16th ecological sources are relatively close. The node centrality of both nodes is high, indicating a strong connection between them. If an ecological path is constructed to connect them, it can effectively improve the overall connectivity of the cross-scale network.

3) For the intersection points along the 19-11 and 5-17 corridors, targeted reforestation and "stepping-stone" habitats are required to boost the efficiency of material exchange across the network.

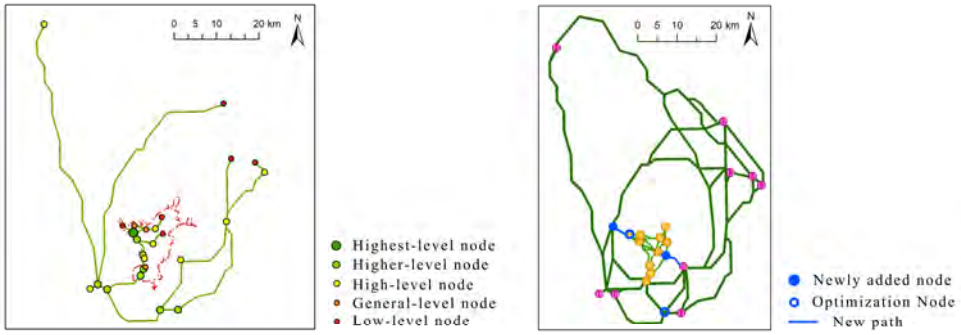

Fig. 6: Optimization plan of ecosystem network

4 Discussion

This study deepened understanding of the scale-transmission mechanism of ecological networks by constructing a systematic analytical process: "ecological source identification – resistance surface construction – cross-scale network integration – key node identification". The identified cross-scale connection key nodes, as spatial hubs guiding macroscopic ecological flows into built-up areas, have significant practical value for the precise restoration of ecological spaces in Hegang City through their priority control.

This study still has certain limitations: the weights of the resistance surface factors are determined by an expert scoring method, which is highly subjective; the analysis focuses on structural connectivity, and indicators reflecting functional connectivity, such as the transmission efficiency of ecological flows, are still insufficiently considered. Future research can introduce machine learning methods to optimize the weight distribution and conduct functional simulation and long-term monitoring verification in combination with the ecological requirements of typical species.

At the practical level, the system analysis framework proposed in this study not only provides scientific support for the ecological transformation of Hegang City but also serves as a reference for other resource-based and shrinking cities. Further work can further distinguish different types of ecological service functions, assess the controllability of each resistance factor, and then formulate more operational hierarchical restoration strategies.

5 Conclusion and Outlook

This study underscores that ecological resilience depends less on the total area of green space and more on the strategic integration of cross-scale paths. By synthesizing MSPA, MCR, and graph theory into a unified diagnostic framework, we have mapped the structural vulnerabilities that single-scale assessments often overlook.

The analysis confirms a stark spatial imbalance: while Hegang is buffered by robust municipal sources, its urban core remains ecologically isolated, tethered to the regional landscape by a precarious "single-path" backbone (Paths 2-5). The identification of Node 2 as a critical

"gatekeeper" provides a clear spatial priority for intervention. Our findings suggest that urban ecological planning must pivot from simple "greening" to "structural reinforcement" – specifically by safeguarding the identified western gateway and fostering redundant paths to mitigate the risk of network collapse.

Ultimately, this research transitions from a purely topological exercise to a practical planning tool. The "strengthening cores, adding paths, and cultivating nodes" strategy offers a scalable logic for other declining industrial or shrinking cities. While this integrated approach clarifies the "where" and "how" of restoration, future inquiries should further explore the dynamic influence of specific species' migration patterns on these resistance surfaces to refine the precision of these ecological linkages.

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Designing like Beavers: A Multi-Agent, Data-Coupled Approach to Process-First Landscape Design for Resilience

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Abstract: This paper presents a DEM-coupled multi-agent prototype that explores beaver-inspired trail formation and canalization as a process-first landscape design method. In NetLogo, the DEM provides slope/aspect fields, and water-tracer particles provide wetness cues during periodic reflooding. Agents generate trails as an intensity field via repeated movement, then excavate on wet cells, accumulating an excavation field that can deepen reinforced corridors into canals. The tool supports scenario comparison rather than prediction: users vary exploration bias, reinforcement/decay, excavation thresholds, slope limits, and reflooding timing, then assess corridor patterns in maps. In a representative case study, simulated trail-and-canal concentrations align with patterns in time-stamped imagery. Limitations include proxy hydrology and no terrain or hydraulic updating; future work couples excavation to flow and morphodynamics.

Keywords: Agent-based modelling, DEM, NetLogo, process-based design, beaver, canals, trails

1 Introduction

Designing for adaptive landscapes requires methods that foreground processes and feedback rather than static forms. The logic of emergence, in which large-scale patterns arise from simple local interactions (STILLMAN et al. 2015). Beavers (*Castor canadensis*) are exemplary ecosystem engineers whose distributed architectures, hydrology, and habitats span water catchments across diverse ecosystems, exemplifying this process-driven approach (NAIMAN et al. 1988, POLLOCK et al. 2014, DOBLER et al. 2025). This engineering feat fundamentally transforms the region's hydrology, vegetation, and biodiversity (BRAZIER et al. 2021). Collectively, beavers engineer a living, adaptive infrastructure that emerges from iteration, feedback, and persistence.

We conceptualize beaver landscape engineering as a process-based system where resilience emerges not from static forms but from dynamic, iterative interactions between behavior and environment. Resilient design arises from its ability to adapt to variations, absorb disturbances, and still remain functional (WALKER et al. 2004). This logic is translated into a digital workbench that enables designers to probe how simple agent rules, acting on real terrain, produce trails, canals, and ponds that can be compared across sites and seasons. By testing designs against landscape constraints, the designer can direct emergent pathways (for water flow and animal migration) that align with ecological goals, driving the co-evolution of human intention and landscape dynamics (TIESKENS et al. 2017).

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While beaver reintroduction efforts yield promising results for riparian restoration (POLLOCK et al. 2014), this approach is often infeasible in urbanized, polluted, or severely degraded contexts (JORDAN & FAIRFAX 2022), necessitating landscape preparation for beavers.

2 Motivation

This tool can support beaver reintroduction by identifying how to prepare landscapes to attract introduced beavers. More broadly, beaver systems model a design logic of distributed, adaptive infrastructure emerging from simple rules, enabling process-first landscape design aligned with ecological goals and dynamics. This contrasts with imposing form without accounting for environmental processes; instead, it supports landscape health by allowing beneficial processes to unfold rather than interrupting them and triggering ecological cascades. With appropriate environmental parameters (e. g., slope, wind exposure, solar orientation), these principles can inform adaptive strategies beyond riparian zones, including deserts, urban environments, and other terrestrial settings.

2.1 Contribution and Scope

The paper asks how beaver-like emergent processes can be simulated to support adaptive, resilient landscape design. We present a beaver-inspired multi-agent, agent-based modeling framework in which simple behaviors interact with an ecologically active environment to generate trail and canal networks (LIU et al. 2021, MATTHEWS et al. 2007, MILLINGTON et al. 2016, STILLMAN et al. 2015, KENNEDY et al. 2024, MURPHY 2025). The tool is exploratory and design-oriented, not predictive, and is intended to test scenarios rather than forecast exact outcomes. It offers an empirically anchored workflow that ingests site data, simulates canalization and connectivity, and evaluates resulting landscape change in terms of hydrologic performance and water retention. Although beavers are known for dams, we focus on resource-driven trail clearing and canal excavation because these processes directly restructure vegetation patterns and redirect flow, informing placement of trails, planting, and infrastructure in ways that reduce disruption to ecological cascades

3 Methods

In this section, we introduce the methodological foundations of our analysis and define the framework. The proposed approach integrates high-resolution topographic data with ABM to simulate the spatial logic of beaver-engineered landscapes. The workflow transitions from data acquisition to an initial behavioral testing phase in NETLOGO.

3.1 Data Preparation and Hydrologic Layers

The simulation environment is built upon high-resolution geographic data to provide an ecologically realistic spatial context for behavioral analysis. Digital elevation models (DEMs) were acquired from the USGS National Map and NOAA Digital Coast repositories, establishing a simulation environment with a spatial resolution of $\leq$1 m. To ensure site authenticity, beaver presence was verified through expert visual confirmation of dams and lodges us-

ing time-stamped satellite imagery, which served as a cross-check for the hydrologic features derived from the topographic data. The data processing workflow transforms these raw surfaces into a structured analysis stack through the following steps:

3.2 Agent-based Framework: Behavioral Prototypes

Beavers are modeled as autonomous agents that switch among discrete modes (explore, forage, return) under a simple energy budget anchored to a home lodge. Each tick follows the same loop: agents select a movement direction from local cues (e. g., wetness/slope), current mode, and optional short-term memory; they move one cell; and the occupied cell updates persistent "design-trace" fields. Patches store (i) trail intensity (cumulative visitation), (ii) canal depth (excavation that increases in water), and (iii) simple infrastructure flags (e. g., is-trail?, is-canal?). When traces exceed thresholds, patches are classified as trails or canals, making emergent infrastructure explicit. Over time, repeated movement and excavation convert individual decisions into landscape-embedded traces that can bias subsequent movement.

We implemented three behavioral archetypes in NETLOGO to isolate distinct infrastructure logics before terrain coupling (see Figure 1). In real systems, hybrid and transitional trails are expected (e. g., exploratory segments that become harvesting corridors, or connector corridors that originate as foraging returns). The taxonomy is to discuss trail morphology.

1. ***Type-1 (Exploratory trails):*** Agents perform correlated random walks in homogeneous vegetation, shaped by two biases: (i) distance-decay trail following (agents probabilistically follow existing trails, with reinforcement decreasing with distance from the lodge via a tunable exponent) and (ii) outward exploration (turns biased away from home while exploring). A bounded memory discourages tight loops. Trails emerge when cumulative visitation intensity exceeds a threshold, with optional fading to remove underused paths. Movement on trails is faster and less costly (scaled by a trail-energy multiplier). The result is a dendritic network: dense near the lodge, with branching increasing outward.
2. ***Type-2 (Directed foraging and canalization):*** Vegetation heterogeneity is modeled as resource gradients formed by quality peaks with Gaussian decay. Agents detect high-quality patches within a base range; when quality exceeds a pursuit threshold, they switch to directed foraging and climb the gradient using forward-cone sampling with capped turns. After harvest, the patch is depleted (and then regrows after a set interval), and the agent returns to the lodge, incrementing a harvest-success counter along the way. Return-path patches convert to canals when success exceeds a threshold, the patch is not already canalized, and it is connected to water or an existing canal via neighbor adjacency. Canal patches deepen at a fixed excavation rate, persist as infrastructure, and reduce transport costs under load more than trails (*canal-energy-multiplier* < *trail-energy-multiplier*).
3. ***Type-3 (Connector trails):*** Water sources are placed interactively by mouse click. Agents detect sources within a fixed radius and, upon detecting an additional source, enter a transit state and move toward the goal. Route choice prefers established paths (high traffic or existing canals) within a vision radius; otherwise, agents move directly. Transit increases patch traffic and incision depth. Patches exceeding a connector threshold canalize when occupied by a transiting agent or reinforced by multiple high-traffic neighbors. Trails decay over time, while canals persist with slow infill unless maintained, producing straight, durable corridors between aquatic nodes.

3.3 NETLOGO Terrain-coupled Prototype (Water-Following Excavation)

This section outlines an initial behavioral testing phase using a NetLogo prototype to stress-test and refine the rule set describing how beaver-like agents interact with a terrain-coupled wetness cue. Evaluation is generative and morphological to assess whether the rules can plausibly reproduce families of trail-and-canal patterns observed in beaver-modified landscapes, rather than predicting the exact location, timing, or magnitude of canal excavation. The simulation serves as a "behavior-plus-accumulation scaffold" that maps movement and persistent traces before introducing physical terrain/aquatic modifications.

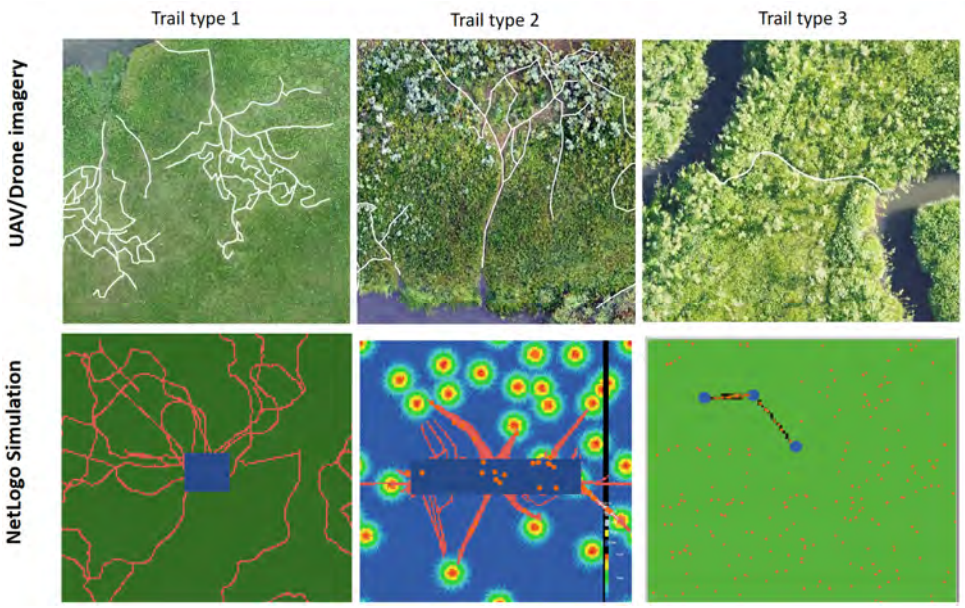

Fig. 1: Trail type morphologies. (Top row) UAV imagery of beaver trail systems (KENNEDY 2023); (Bottom row) NETLOGO simulations' outputs of trail types. Trail type 1 emerges in a homogenous vegetation structure, Trail type 2 emerges with a heterogeneous vegetation structure, and Trail type 3 occurs when connecting water bodies.

Environment and Calculation. The model is initialized by loading a DEM via the NETLOGO GIS extension. Local terrain characteristics, i. e., slope and aspect (direction), are calculated using 3x3 convolution kernels, allowing agents to know the gradient.

Agent Breeds and Logic. The simulation defines two distinct types of entities:

- *Water-drops:* These are numerous particles that spawn across the map and move according to the local aspect to simulate drainage. Water-drops are passive entities that model site drainage, representing the backend that allows the evolution of the DEM.
- *Erosion agents (Excavators):* These are the active agents that interact with the environment. Excavators are mobile agents (beavers) that follow the water particles and act on the environment according to a set of user-defined behavioral rules.

The "Chase Water, Dig on Water" Rule. Such a set of behavioral rules consists of a movement logic (Finite State Machine – FSM) governed by a simple decision rule: *excavators must remain in contact with water-drops.* From this, a set of *actions* follows:

- *Excavation*: When an agent occupies a "watery" patch, it increments an "erosion-count" for that cell, simulating riparian erosion.
- *Pathfinding:* If an agent becomes "dry," it may "jump" to the nearest water source to continue its task. This rule models beavers' preference for staying in water environments. The system evolves in time by iterating this FSM for a predefined number of steps. Lastly, the simulator respawns water every 730 ticks to mimic seasonal flooding, where every 2 ticks represent a single day. The first iteration of this tool is limited to northern inland regions with high snowpack. After 730 ticks, beaver-agents respawn from locations on the established heatmap, aligning with the springtime beaver migrations.

Parameter selection is treated as part of the design workflow. Most parameters are expressed in patch units and interpreted as transparent design levers (e. g., exploration bias, trail reinforcement/decay, excavation thresholds, reflooding cadence). These levers are tied to site attributes: DEM resolution sets the spatial grain; slope and aspect derived from the DEM define the drainage cue that water-drops follow; and the reflooding represents an annual hydroperiod (e. g., spring snowmelt) appropriate to the study region. We recommend reporting the default parameter set alongside a small one-at-a-time sensitivity screen that identifies which corridors and canalization hotspots persist across parameter ranges.

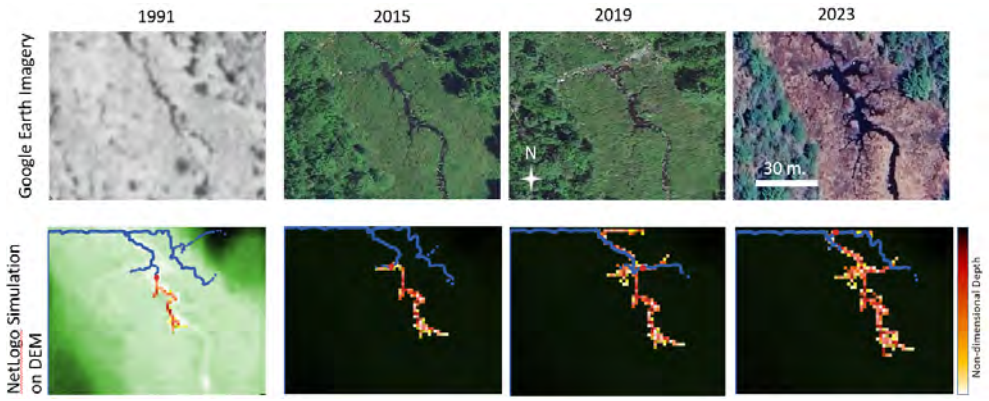

Fig. 2: Canal evolution. Top (Google Earth satellite imagery: 44.365891°, -68.273084°) shows evolution of a beaver canal network. Bottom (NETLOGO output of DEM from 2010 showing heatmap evolution of agents "chasing" water. Blue is water.

3.4 Outputs and Metrics

Each run produces cartographic outputs (trail intensity, canal depth, connector corridors, depleted/regrown vegetation). It also outputs scalar reporters for scenario comparison: counts of trail/canal patches, woody/edible/depleted vegetation, behavioral state distributions, average carrying load (Type-2), and canal formation (Type-3). Because the prototypes represent trails/canals as stateful fields rather than explicitly updating terrain and hydraulics, we frame the method as a workbench for identifying corridors and intervention windows (patterns that persist across parameter values), rather than a predictive geomorphic forecast. We derive two minimal morphological descriptors from thresholded trail/canal fields: (i) path density (the fraction of patches classified as trail or canal) and (ii) branching index (mean node degree after skeletonizing the binary network, with nodes defined at junctions and endpoints). These are descriptive rather than predictive, providing compact summaries for comparing scenarios and checking whether simulated networks fall within a comparable range of density and connectivity to observed beaver landscapes.

4 Results (Representative Site)

4.1 Local Trail Building and Reinforcement: Beavers Harvest Vegetation

1. ***Type-1 (Exploratory trails in homogeneous fields):*** Exploration-driven trails structurally matched the patterns observed in beaver habitats characterized by homogeneous vegetation gradients. The correlated random walk algorithm with distance-decay preferences and outward biasing produced radial trail networks emanating from a central lodge.
2. ***Type-2 (Directed foraging with resource gradients):*** In heterogeneous vegetation landscapes with multiple quality peaks, agents demonstrated gradient-following behavior. Woody patches were targeted, harvested, and allowed to regenerate. Outbound foraging paths accumulated trail-intensity markers; successful harvests added harvest counters along each path segment. When cumulative harvest exceeded threshold values and paths connected to water/canal frontiers, eligible trail cells converted to canals.
3. ***Type-3 (Connector trails between water bodies):*** When multiple water sources were placed interactively in the simulation domain, agents detected water sources within a specified radius and switched from local foraging to direct transit between nodes. Transit routes preferentially select high-traffic cells or direct paths. Cumulative traffic along these routes incremented patch-level traffic and incision depth counters. When traffic exceeded connector thresholds and local cell alignment indicated sustained directional movement, trails canalized into semi-permanent links with lower decay rates.

4.2 Global Damming Complex Networks: Beavers Chase Water

To assess morphological plausibility against real-world beaver infrastructure, we integrated NOAA DEM imagery from Acadia National Park (2010) with historic Google Earth imagery spanning 2011-2023. We compare simulated canal-depth fields to the observed stream and canal signatures via visual overlays (Figure 2) and simple descriptors (path density and branching), emphasizing pattern correspondence rather than prediction. The purpose is to demonstrate how a DEM-coupled ABM can operate as a design aid for exploring where canalization tends to concentrate under terrain constraints.

Outputs and Limitations: This system, at present, only works well on well-defined drainage networks with single local minima. Multiple local minima often lead digital agents to build canal systems in areas where water does not exist in the real world. To make this system more robust, further implementation of this tool will require correctly classifying streams from land, a task that requires human-annotated topographic maps. Furthermore, erosion rates in natural systems are tied to the material properties of soil, vegetation structure, and moisture content, creating heterogeneous erosion rates. This tool is only capable of a first order approximation of erosion rates due to agent behaviors.

5 Discussion

5.1 Design Insights

This workbench is useful as a process-tuning tool rather than a form generator. Instead of drafting canal geometries a priori, designers set boundary conditions and adjust a small set of interpretable levers (exploration bias, reinforcement/decay, excavation thresholds, re-flooding cadence). The model returns trail-intensity and excavation fields that act as design traces, ultimately showing where corridors repeatedly concentrate and where canalization tendencies persist across runs. Terms like “evaluation” and “validation” refer to these pattern-based plausibility checks and comparative summaries, not to empirical calibration for ecological prediction.

5.2 Limitations and Next Steps

Hydrology is a proxy: tracer-based wetness cues do not resolve depth or velocity. Trails/canals are represented as stateful fields without terrain or hydraulic updating. Vegetation dynamics are simplified and do not encode functional groups or harvesting/regrowth. Spatial outcomes are bounded by DEM cell size and vertical accuracy; shallow canalization may fall below the detection threshold at coarse resolutions. Next steps include to couple excavations to hydraulics, introducing seasonal hydroperiods and material economies, and extending dams. This work will be moved to a more robust modeling platform, Python’s Mesa, to integrate the multiple layers of ecological, hydrodynamic, and behavioral patterns, to study more complex systems.

6 Conclusion and Outlook

The paper demonstrates a reproducible digital method that operationalizes computation in service of ecological resilience. By embedding feedback as design material, the approach links behavior, terrain constraints, and canal/trail networks on real landscapes. Exploratory rather than predictive, the method generates hypotheses about where animal-like excavation can most improve water storage, refugia, and connectivity, enabling a process for human–nonhuman co-design in digital landscape architecture.

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Geospatial Analysis, Urban Ecology and Planning

A Threshold-Driven Method to Urban Ecological Security Zoning Management: The Case of Green Infrastructure Planning in Harbin, China

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Abstract: Ecological vulnerabilities in cold-region legacy industrial cities remain poorly addressed by conventional management, which frequently lack the quantitative threshold guidance necessary for effective intervention. To bridge this critical gap, this research uses Harbin as a case study to develop a comprehensive "assessment-identification-zoning-application" framework, operationalizing a threshold-driven approach to ecological security. The investigation integrates the Pressure-State-Response model to evaluate the Urban Ecological Security Index (UESI), employing Geo-Detectors for driver screening and generalized additive models to pinpoint precise ecological security thresholds. Analysis reveals that Harbin's ecological integrity is primarily dictated by climatic variables – specifically winter ground surface temperature (GST win) and annual precipitation (PRE ann) – which function through significant nonlinear synergies. These natural drivers markedly amplify the stress caused by anthropogenic disturbances such as building density and air quality degradation. By applying a two-dimensional state-stability coupling matrix, the study delineates Harbin into six distinct functional zones, ranging from ideal safety to extreme danger. This spatial differentiation directly informs a tailored green infrastructure planning strategy for each zone. Ultimately, this work converts abstract threshold theory into a pragmatic spatial instrument, providing rigorous quantitative benchmarks for territorial planning and nature-based resilience restoration in cold-region urban contexts.

Keywords: Threshold, nature-based solutions, Urban Ecological Security, spatial zoning, green infrastructure planning

1 Introduction

Rapid urbanization and socioeconomic development pressure pose a severe threat to urban ecosystems (LU et al. 2025). Protecting urban ecological security has become a core challenge for sustainable development and a critical issue for Nature-based solutions (MCPHEARSON et al. 2025). This problem is particularly acute in cold-region legacy industrial cities: the high-latitude and frigid climate results in scarce urban green spaces, which leads to low per capita green coverage (AN et al. 2025); while the presence of industrial brownfield and high-density urban built-up areas severely fragments ecological patches. Existing research indicates that the ecosystems of traditional industrial cities in cold regions possess unique vulnerabilities; they are not only more sensitive than ecosystems in other urban environments but also closer to the point of irreversible degradation (BAI & XING 2025). Irreversible degradation refers to the fundamental changes in the structure and function of urban ecosystems after crossing the ecological security threshold, which cannot be restored through natural processes within a reasonable social time scale and must rely on high cost human intervention. The significant spatial heterogeneity of ecological conditions along the

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urban-rural gradient exacerbates this inherent vulnerability. Therefore, standardized management strategies are insufficient to meet the specific needs of different regions. Previous studies have primarily focused on examining the seasonal fluctuations of local ecosystem services or assessing ecological security from the perspective of land-use change (OUYANG et al. 2024, ZHU et al. 2025). However, traditional research methods exhibit significant limitations in ecological management: they often rely on simplistic quantitative analysis, static assessments, or decision-makers' experiential judgments, lacking ecological security thresholds (ESTs) that guide optimal timing for management interventions (SONG et al. 2024). ESTs denote the critical values at which urban ecosystems undergo irreversible structural-functional changes during transitions from their original steady state to a new one under natural or anthropogenic disturbances (H. LI et al. 2026). This absence of thresholds makes it difficult for decision-makers to identify the critical points where ecosystems transition from quantitative to qualitative changes. Action is often taken only after urban ecological problems become irreversible, resulting in management lag. Therefore, identifying ESTs for cold-region old industrial cities has become particularly urgent.

To address this challenge, this study aims to answer a key scientific question: How can a threshold-driven ecological security zoning management approach be established for cold-region old industrial cities? Specifically, how can ESTs in these cities be precisely identified to enable forward-looking spatial zoning and planning interventions? To solve the problem, this research establishes a progressive framework structured around four interconnected objectives. The evaluation objective constructs a Pressure-State-Response model designed to diagnose ecosystem health and quantify the spatial differentiation of ecological security levels specifically within cold-region legacy industrial cities. Following this, the identification phase leverages Geo-Detectors and generalized additive models to reveal nonlinear driving mechanisms and pinpoint precise security thresholds that function as critical early warning signals for policy intervention. These quantitative benchmarks directly inform the zoning objective, which delineates urban space into functionally oriented management units based on ecological stability. Ultimately, the application phase bridges the gap between theory and practice by translating these spatial findings into actionable green infrastructure planning strategies.

2 Data and Methods

2.1 Study Area and Data Sources

This study conducts an empirical analysis using Harbin as a case. Located in northeastern China (E125°42′-130°10′, N44°04′-46°40′), Harbin is a typical cold-climate megacity and a representative case of transformation from an old industrial base. Its ecological security is threatened by multiple factors: urban expansion, the weak self-repair capacity of ecosystems in cold climates, industrial pollution, and an extreme shortage of green space in the urban core. The ecological security pattern is influenced by multiple factors, including rapid urbanization, the distribution of industrial heritage sites, and the hydrological characteristics of the Songhua River basin. For these reasons, Harbin was selected as a representative case study for cold-region, legacy industrial cities. The study area encompasses the six urban districts of Harbin (Fig. 1), covering a total area of approximately 5,016 square kilometres. This study employed multi-source heterogeneous data, including 30-meter resolution China Land Cover Data (CLCD) and Digital Elevation Model (DEM), 100-meter resolution population density

data, 250-meter to 1-kilometer resolution Normalized Difference Vegetation Index (NDVI) and Net Primary Productivity (NPP), 500-meter resolution NPP-VIIRS nighttime light data, and approximately 10-kilometer resolution precipitation, surface temperature, and soil moisture data (NetCDF data).

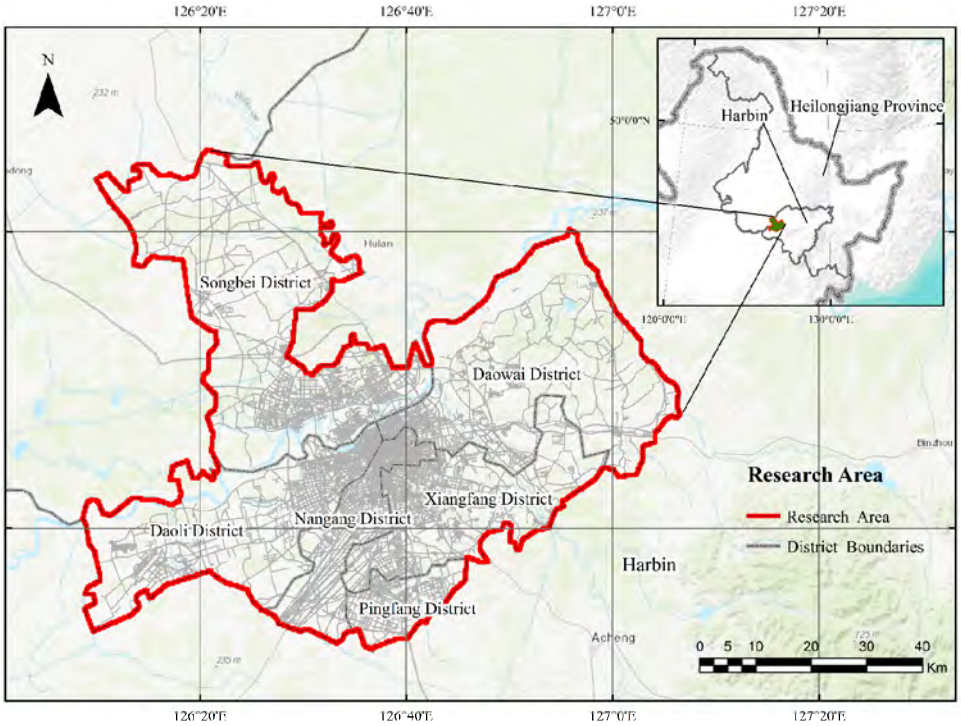

Fig. 1: Study area

Additionally, vector data from OpenStreetMap encompassing building density, road networks, green spaces, and industrial land use were incorporated. Except for vector data, all raster data were resampled to a uniform 1000-meter resolution in ArcGIS and used as the basis for statistical analysis. All data was collected in 2020 – 2024.

2.2 Methods

The study follows the logical framework of "assessment – identification – zoning – application," with the specific steps outlined below.

2.2.1 Urban Ecological Security Assessment

Based on the "Pressure-State-Response" (PSR) framework (NAN et al. 2025), 12 indicators were selected for Urban Ecological Security Assessment (UESA), establishing the Urban Ecological Security Index (UESI). PSR systematically quantifies human-induced environmental pressures, the current state of ecosystems, and societal responses to improve environ-

mental conditions. The UESI serves as the framework's final quantifiable, weighted output, measuring the comprehensive security level of each unit. Using the ArcGIS Fishnet tool, the study area was divided into 1,413 grid cells, which formed the basic units for UESI calculation and all subsequent analyses. Subsequent analyses were conducted based on this grid structure. The UESI calculation formula is as follows:

$$UESI_j = \sum_{i=1}^{n} w_i \times S_{ij} \quad (1)$$

Among these, $UESI_j$ represents the composite index value for grid cell j; w_i represents the composite weight for indicator i; and S_{ij} represents the standardized indicator score.

The stress layer integrates population density, road network density, and nighttime light intensity to reflect the magnitude of anthropogenic stress. To assess the current environmental status, the state layer integrates net primary productivity and various landscape pattern indices; these spatial indicators are calculated using Fragstats software based on land use datasets (CUSHMAN et al. 2008); Finally, the response layer quantifies the effectiveness of management and policies through indicators such as green space accessibility and ecological compensation investment. To scientifically determine weights, a comprehensive weighting method combining the Analytic Hierarchy Process (AHP) and Entropy Weighting Method (EWM) was employed (NAN et al. 2025). AHP determines the strategic importance of indicators based on expert consultation, while EWM reflects indicator discrimination based on data dispersion. Final weights were integrated through weighted averaging and validated via consistency tests and collinearity diagnostics. Additionally, sensitivity analysis of indicator weights was incorporated, and the robustness of UESI ranking results was verified by fine-tuning weight parameters.

2.2.2 Driving Factor Screening and ESTs Identification

We used Geo-Detector to identify key drivers and their interactions without assuming linear relationships, GAMs to flexibly fit nonlinear UESI responses and pinpoint thresholds via derivative analysis. Compared with Random Forest and other machine learning methods, GAMs avoids the black-box of machine learning and the rigid forms of parametric nonlinear models.

The study uses the Factor Detector within Geo-Detector to screen the nine candidate indicators, and then to identify the driving factor with the strongest explanatory power for UESI spatial differentiation. Subsequently, employ the Interaction Detector to identify synergistic interactions between different factor pairs, thereby determining the optimal driving factor for threshold identification (ZHANG et al. 2025). For Geo-Detector analysis, continuous variables were discretized into six levels using the natural break-point method. Generally, researchers prefer interpretable methods over machine learning approaches due to their specific advantages in analysing spatial hierarchical heterogeneity and detecting interactions.

The R package mgcv was used to construct generalized additive models (GAMs), fitting nonlinear response curves between UESI and key factors. The calculation formula is as follows:

$$Y = \beta_0 + s(X_1) + s(X_2) + \cdots + \varepsilon \quad (2)$$

Where s denotes the smoothing function. By analysing changes in the first or second derivatives of the smoothing function, inflection points within the response curve can be accurately

identified. Compared to traditional linear models, parametric nonlinear models, or machine learning models, GAMs outputs can be conveniently plotted as response curves, allowing researchers to directly observe trends in UESI as a specific indicator varies (DETMER et al. 2025). By analyzing the inflection points and intervals of significant slope changes in the curve, critical thresholds where ecological security states undergo qualitative changes can be identified. Combining these critical points from the response curve with a 10% sample bandwidth enables the identification of ESTs, which serve as the scientific basis for subsequent zoning.

2.2.3 Threshold-Driven Ecological Security Zoning

Based on the dual-dimensional coupling of threshold responses to driving factors and UESI assessment results, a "state-stability" zoning matrix is constructed. First, the ESTs state evaluation is conducted. Using thresholds identified from GAMs response curves, each core factor within every grid cell is classified into one of three states: Safe (S), Critical (C), or Dangerous (D). A combined evaluation method categorizes the stability of driver factor states into three distinct tiers: High (Threshold) indicates strong synergistic stability and disturbance resistance; Medium (Threshold) indicates ecosystem vulnerabilities or critical equilibrium; and Low (Threshold) indicates susceptibility to structural-functional degradation. Following this categorization, the assessment employs the natural breakpoint method to classify UESI values into five segments. To highlight ecologically superior areas, the top three high-score segments are defined as "High (UESI)", while the bottom two low-score segments are designated as "Low (UESI)".

Finally, a two-dimensional coupled matrix is constructed. Spatial zoning is achieved through a 2x3 decision matrix (Tab. 1), which divides the study area into six security zones: (1) Ideal Security Zone (High-High), (2) Potential Risk Zone (High-Medium), (3) Critical Hazard Zone (High-Low), (4) Restorative Security Zone (Low-High), (5) Degraded Vulnerability Zone (Low-Medium), (6) Extreme Danger Zone (Low-Low).

2.2.4 GI Planning Application

The above zoning results establish an actionable green infrastructure planning strategy framework that translates quantitative analysis into spatial guidance. This framework provides an integrated approach to territorial management and provides tailored green infrastructure configuration recommendations for each distinct zone.

Table 1: Two-Dimensional Coupled Matrix

Comprehensive Score	High (Threshold)	Medium (Threshold)	Low (Threshold)
High (UESI)	Ideal Security	Potential Risk	Critical Hazard
Low (UESI)	Restorative Security	Degraded Vulnerability	Extreme Danger

3 Results

3.1 PSR Indicator Selection and Modelling

Table 2: PSR Modelling: "+" indicates a positive effect on UESI; "–" indicates a negative effect

Criterion layer	Indicator layer	Significance	Symbol	Weight
Pressure	Population Density	Reflects the resource consumption and environmental pressures resulting from population concentration.	–	0.0774
	Nighttime Light Intensity	Reflects the intensity of human economic activity and the physical footprint of urban sprawl.	–	0.0727
	Distance to Industrial Land	Reflects the spatial dispersion pressure of industrial pollution sources.	+	0.3352
	Road Density	Reflects the degree of habitat fragmentation and fragmentation pressure caused by road infrastructure	–	0.0546
State	NPP	Core health indicators characterizing ecosystem carbon sequestration capacity and energy flow.	+	0.0546
	Patch Density (PD)	Reflects the degree of landscape fragmentation, higher density typically indicates poorer habitat connectivity.	–	0.0241
	Shannon's Diversity Index (SHDI)	Reflects Landscape Heterogeneity and Structural Complexity	+	0.0601
	Distance to Major Water Area	Reflects the coupling degree of blue-green spaces, proximity to water bodies helps maintain local ecological balance.	–	0.0138
Response	Green Space Accessibility	Reflects the accessibility of ecological services for residents and the effectiveness of green infrastructure.	+	0.1203
	Proportion of Green Line	Reflects the enforcement strength of urban green line control policies and ecological protection boundaries.	+	0.0464
	Surface Perviousness Rate	Reflects surface runoff regulation capacity.	+	0.0376
	Heat Island Mitigation	Reflects the ecological capacity to mitigate the urban heat island effect.	+	0.0928

This research constructs an evaluation framework founded on the Pressure-State-Response model, utilizing twelve indicators systematically distributed across three primary dimensions (Tab. 2).

Indicator weights derive from a hybrid approach combining the Analytic Hierarchy Process with the Entropy Weight Method, a configuration that effectively balances the qualitative insights of expert judgment against the quantitative dispersion of objective data.

3.2 UESI Calculation

After completing indicator standardization, the study area was divided into 1,413 grid cells using the 1000m resolution grid tool from the ArcGIS toolbox. 1,413 grid cells serve as the basic research units. A multi-factor weighted integration method calculated the Urban Ecological Security Index (UESI) for each unit based on the established comprehensive weights, as illustrated in Figure 2. Statistical validation confirms the reliability of this framework through two key indicators. First, the average consistency ratio of the AHP scoring matrix indicates a value of (CR = 0.064 < 0.1), which satisfies all requirements for logical consistency. Second, the variance inflation factors (VIF) indicate values ranging from 1.25 to 3.82, which confirms the absence of significant multicollinearity and demonstrates the robust performance of the integrated model.

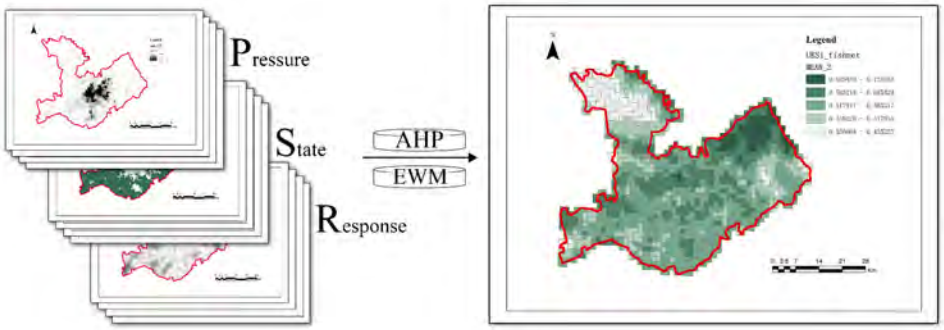

Fig. 2: UESI result

3.3 Screening of Driving Factors Based on Geo-Detector Analysis

Geo-Detector analysis confirms that all candidate factors drive the spatial differentiation of the Urban Ecological Security Index (UESI) at a statistically significant level ($p < 0.05$). The factor detection phase reveals that the explanatory power of each indicator, quantified through q-statistics, exhibits distinct gradient variations across the assessment framework. The top four core driving factors ranked by explanatory power were winter ground surface temperature (GST_win, q = 0.353), annual precipitation (PRE_ann, q = 0.309), air quality index (AQI, q = 0.259), and winter precipitation (PRE_win, q = 0.228). Other factors such as annual ground surface temperature (GST_ann), and NDVI also demonstrated some explanatory capacity, but with relatively lower q values. Infrastructure density (ID) exhibited the lowest explanatory power (q = 0.043). Data distribution characteristics indicate that climatic elements, represented by ground temperature and precipitation, exert the most extensive influence on the spatial pattern of UESI. Meanwhile, building density (BD), as a key indicator measuring the development intensity of built-up areas, ranks first in explanatory power among socioeconomic (anthropogenic disturbance) factors. The visible results are shown in Figure 3.

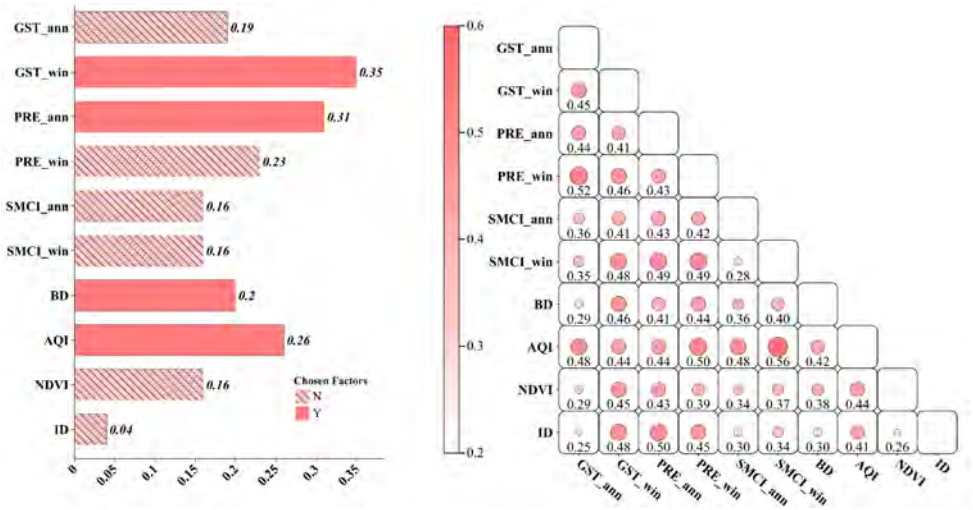

Fig. 3: Results from Factor Detectors (left side of the image) and Interaction Detectors (right side of the image)

In the interaction detection section, the explanatory power of any two interacting factors consistently exceeds that of either factor acting independently, with bi-enhancement being the predominant interaction type. The most significant explanatory gain occurs when natural background factors interact with social disturbance factors. Notably, although BD ranks fifth in single-factor explanatory power, its coupling with natural factors exhibits pronounced nonlinear enhancement and bi-enhancement characteristics. Among all combinations, the interaction between GST_win and BD yields the highest q-value of 0.463. Additionally, combinations such as AQI with BD (q = 0.416), PRE_ann with BD (q = 0.412), and climate factor pairs like GST_win with AQI (q = 0.442) and PRE_ann with AQI (q = 0.445) all demonstrated high explanatory levels.

Statistical results indicate that the spatial heterogeneity of Harbin's urban ecological security may be jointly driven by climatic factors and urban development intensity, with their combined effects significantly enhancing the explanatory power for security pattern differentiation. Therefore, this study selects GST_win, PRE_ann, AQI, and BD – which plays a core amplifying role in the interaction mechanism – as driving factors.

3.4 ESTs Identification Based on GAMs

This study employed the mgcv package in R to construct a generalized additive model, capturing the nonlinear response characteristics of the UESI index to four drivers (PRE_ann, AQI, GST_win, BD) identified by the Geo-Detector. Restricted maximum likelihood (REML) was employed for parameter smoothing to prevent overfitting. The model explained 49.8% of the variance, with an adjusted R^2 of 0.487. All driving factors' smoothing terms yielded p-values < 0.001 in significance tests, confirming nonlinear model's suitability for identifying complex ecological responses. From the fitted smooth curves, ESTs were identified based on first-derivative analysis: inflection points (where slope changes most rapidly), local extrema (UESI maxima or minima), and stabilization points (where the curve flattens). These candidate points were adopted as ESTs.

In practice, ecological transitions do not occur at a single value. To account for this uncertainty and provide a precautionary management buffer, we defined a critical state as any factor value falling within a ±10% sample bandwidth around the ESTs. This 10% bandwidth follows common practice in ecological threshold research (SONG et al. 2024) and reflects typical ecological resilience and decision margins.

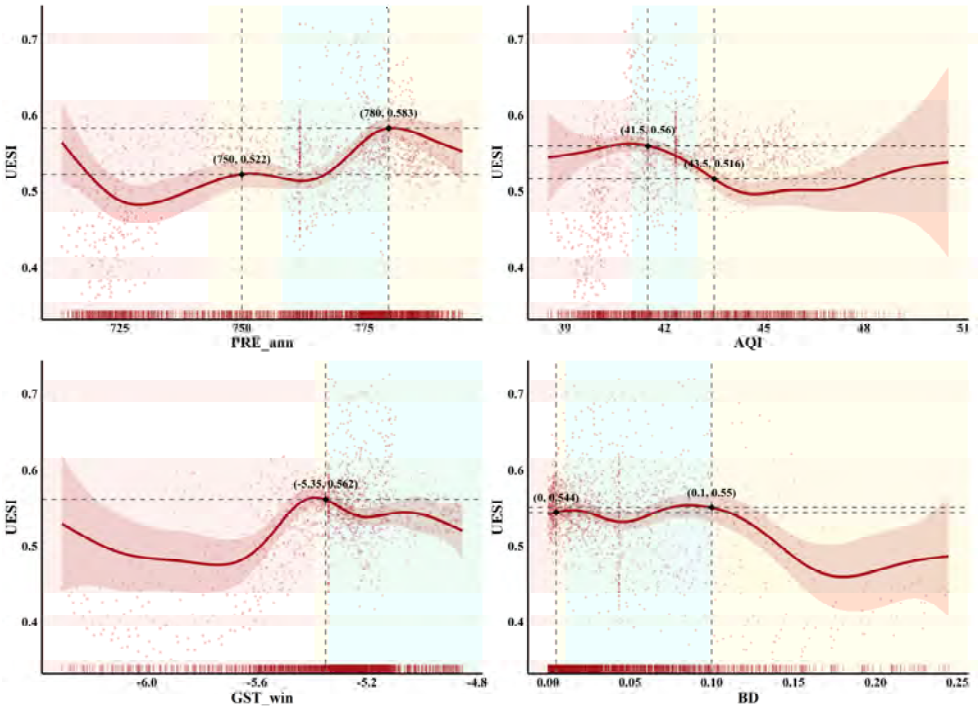

Fig. 4: Response Curves and ESTs of UESI to Selected Driving Factors

By analysing changes in the curve's derivative (slope) and extrema points, combined with a 10% Sample Bandwidth, four ESTs of driving factors were identified: PRE_ann curve reflects an inverted U-shaped response where UESI peaks at 750 mm and declines sharply once values exceed 780 mm. AQI curve reflects an optimal range between 41.5 and 43.5 that denotes a critical turning point in ecosystem sensitivity to pollution stress. GST_win curve reflects a rising trend toward stabilization at -5.35 ℃, a threshold below which ecosystem vitality experiences periodic degradation, and BD curve reflects a rigid development limit with a primary inflection point at 0.005 and a precipitous decline once values surpass 0.10.

3.5 Ecological Security Zoning Based on Two-Dimensional Coupling Matrix

Based on the identified thresholds and the 10% sample bandwidth rule, the study classes the factor status of each grid cell into three categories: Safe, Critical, and Dangerous. The green region represents the safe state, the yellow region represents the critical state, and the red region represents the dangerous state:

1) Safe State (Safe, S): Refers to factor values within the interval where the UESI bias effect is highest and stable. For example, GST_win > -5.35 ℃ on the right side of the bandwidth, or BD within the interval (0.005 bandwidth right side, 0.10).

2) Critical State (Critical, C): Refers to factors fluctuating near threshold points (within 10% bandwidth of sample size) or within the inflection zone of a downward UESI trend. For example, PRE_ann > 780 mm is defined as critical risk.

3) Dangerous (D): Indicates the factor value is within the UESI low-response zone or a region of steep slope decline. For instance, marginal states where BD < 0.005 (extreme vacancy) or BD > 0.10 (excessive development).

This regional classification of threshold states can be observed in Figure 4.

For each grid cell, the driving states of its four thresholds are collected and combined to determine the SCD (Safe-Critical-Dangerous) assessment level. The SCD assessment employs a composite evaluation method, categorizing the 1,413 grid points into three classes: High: Includes combinations of 4S, 3S1C, and 2S2C (633 grid points total), indicating relatively stable conditions. Medium: Includes combinations such as 3S1D, 1S3C, and 4C (317 grid points total), indicating potential instability. Low: Includes combinations with multiple D states or a high proportion of C states (463 grid points total), indicating poor condition.

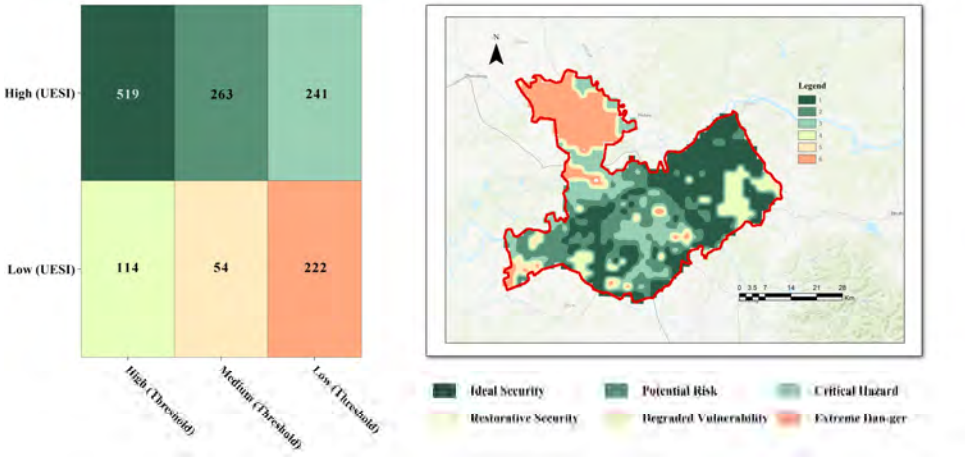

Fig. 5: Ecological Security Zoning Matrix and Zoning Map

To identify the stability of Harbin's urban ecosystem, the UESI assessment results were divided into five categories using the natural breakpoints method and then re-clustered into two states. The top three high-score segments were defined as “High” (1021 grid points), representing relatively good ecological stability; the bottom two low-score segments were defined as “Low” (392 grid points), representing relatively poor ecological stability.

By constructing a 2x3 decision matrix, 1,413 grid points were classified into six ecological security zones (Fig. 5). Statistical analysis reveals: The Ideal Security zone occupies the largest proportion, predominantly distributed in the Ash River area east of Harbin and partially

in the Qun Li New District west of the city. This zone features intact green patches, low population density, and high ecological carrying capacity. Potential Risk zones primarily occupy the suburban transition belt, encircling the city centre in a ring-like pattern. Potential risk zones represent areas of moderate population density that face escalating ecological pressure relative to ideal safety regions. Critical hazard zones probably represent the urban core and feature the highest population density and severe winter air pollution. Restorative Security and Degraded Vulnerability zones are primarily located in heavy industrial areas or old industrial districts such as Harbin Power Plant and Boiler Plant, where ecological stability faces severe challenges. Extreme Danger zones are concentrated in SongBei District, an area with weak infrastructure and undergoing development. Severe pollution caused by urban development and highly fragmented landscapes constitute its extremely high risk.

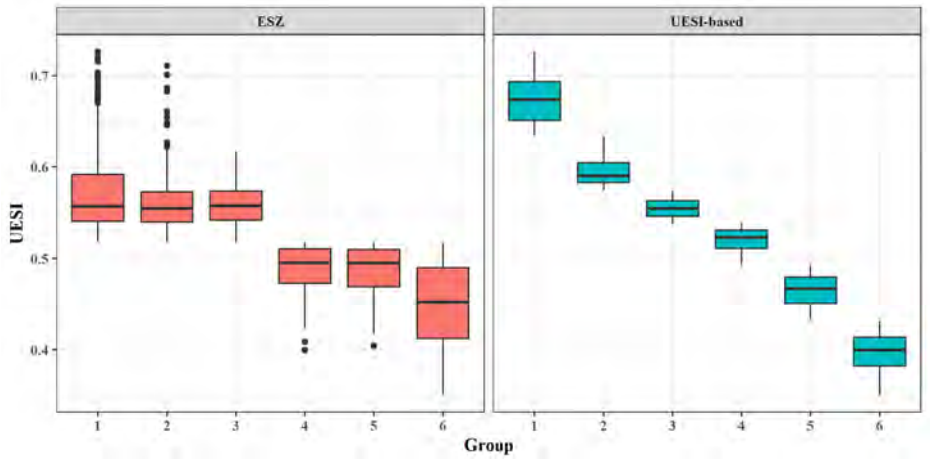

Fig. 6: Comparison of UESI distributions: ESZ (left) vs. UESI-based Jenks classes (right)

We acknowledge that single-indicator correlation is theoretically inappropriate for validating multi-threshold emergent patterns. To assess the robustness of the threshold-driven zoning, we conducted two validation checks. Internally, we compared ESZ's intraclass variance against a purely numerical classification (UESI-based Jenks), confirming that our approach retains 59.6% of UESI variance while enhancing interpretability. Externally, we verified spatial plausibility through qualitative alignment with established nature reserves, industrial brownfield, and documented pollution hot spots. The ESZ exhibited a larger average intra-class variance (0.00119) than the Jenks classification (0.00031), as the latter directly minimizes within-group dispersion. Despite this, a one-way ANOVA showed that ESZ still explains 59.6% of the UESI variance ($R^2 = 0.596$, $p < 0.001$), indicating it retains the main UESI gradient while providing explicit ecological rules. Sample sizes across the six ESZ are reasonably balanced, supporting robustness. Figure 6 presents box plots of UESI under both schemes. The result confirms that the moderate loss in numerical purity is compensated by enhanced interpretability for planning.

3.6 GI Planning Application: Translating Zoning into Actionable Strategies

Table 3: Threshold-Driven Planning Strategies for Ecological Security Zones

Zone Type	Core Objective	Strategies (Based on Identified Thresholds)
Ideal Security	Strict Protection & Core Habitat Conservation	1. Ecological Space Proportion: >95%. 2. Development Intensity Red Line: Building Density (BD) < 0.05.
Potential Risk	Buffer Zone Construction & Risk Prevention	1. Green Space Ratio Increase: Raise from current ~25% to 38-40%. 2. Development Control: BD < 0.08 for new construction areas. 3. Park Service Radius: Achieve 100% coverage within a 300-meter service radius of community parks.
Critical Hazard	Urgent Mitigation & High-Intensity Remediation	1. Pollution & Climate Early Warning: Trigger emergency response when AQI > 43.5 or Winter Ground Surface Temperature (GST_win) < -5.35 ℃. 2. Vertical Greening: Green roof/wall coverage on suitable buildings ⩾ 30% reducing hazards from pollution.
Restorative Security	Priority Restoration & Structural Investment	1. Security Level Improvement: Increase UESI index by > 0.2 within 10 years. 2. Brownfield Conversion: Transform industrial legacy sites into multifunctional green spaces. 3. Core Patch: Restore or establish a core ecological patch > 50 hectares in each sub-area.
Degraded Vulnerability	Systemic Improvement & Adaptive Management	1. Composite Indicator Improvement: Surface perviousness rate > 60% and green space accessibility < 500 meters. 2. Stormwater Resilience: Stormwater retention facilities designed for rainfall events up to 780 mm (PRE_ann).
Extreme Danger	Urgent Intervention & Land Use Restructuring	1. Development Moratorium: Immediately suspend new construction projects with BD > 0.10. 2. Mandatory Ecological Conversion: Any redevelopment project must convert ⩾20% of its site to ecological functions.

One objective of this study is to bridge the gap between ecological security assessment and spatial planning. Based on six ecological security zoning maps (Fig. 5) and identified critical thresholds, this section translates the zoning results into a spatially explicit green infrastructure (GI) planning strategy framework (Tab. 3). Notably, the “Development Moratorium” proposed for Extreme Danger zones represents a necessary policy instrument. It shifts urban management from reactive mitigation to proactive rigid control, providing a clear red line for preventing irreversible degradation in the most vulnerable areas.

This framework aims to provide actionable guidance for Harbin's territorial spatial planning and ecological restoration projects (BAI & XING 2025).

4 Discussion

This study establishes ecological security thresholds as a pragmatic instrument for urban spatial zoning management by converting a theoretical framework into an operational tool. It also establishes that ecological security within cold-climate cities depends not merely on the resulting index value but on the underlying regulatory influence of key driving factors on the ecosystem. For instance, Restorative Security zones characterized by low indices and high stability demonstrate that low-scoring areas can possess high regulatory potential and cost-effectiveness for interventions.

The analysis confirms that unique ecological driving mechanisms characterize cold-region legacy industrial cities. Within these environments, climatic background factors – specifically winter ground surface temperature and annual precipitation – represent the dominant drivers of spatial differentiation. Conversely, socioeconomic factors represent secondary influences, as climatic q-statistics significantly surpass those of anthropogenic variables. This hierarchical driver structure contrasts sharply with the patterns observed in mid-to-low latitude cities, where socioeconomic development often dictates ecological security. Key specifics include: 1) Winter cold imposes a rigid constraint; UESI increases with GST_win and stabilizes near -5.35℃, marking a functional transition (SUN et al. 2025); 2) Precipitation shows an inverted U-shaped response, with a fragile equilibrium between drought and flood stress at 750-780 mm; 3) Winter solid precipitation exhibits an "accumulation-release" effect, its impact more fully captured at the annual scale, indicating a need for more precise monitoring indicators (AN et al. 2025).

Analysis identifies a nonlinear synergistic effect between natural stressors and anthropogenic disturbances as a defining characteristic of regional ecological vulnerability. Under winter conditions, negative impacts from urban development intensity (BD) and industrial pollution (AQI) are amplified (LEE et al. 2024). The interaction explanatory power between GST_win and BD (q=0.463) exceeded the sum of their independent effects. The AQI and GST_win interaction (q=0.4415) was also significant. Industrial pollutants disperse via monsoons, exacerbating smog. The AQI threshold (~41.5-43.5) identified by GAMs may indicate that when pollution concentrations exceed this critical range, not only does air purification capacity accelerate its degradation, but it also directly triggers public health risks – winter haze more readily leads to respiratory diseases. The impact thus extends from natural ecosystems to human health (ZENDER-SWIERCZ et al. 2024).

These findings offer new perspectives for understanding these cities. Limitations exist: First, while the 1km grid analysis effectively captures macro-level patterns, it has limitations in guiding detailed GI design at the neighborhood scale, such as pocket parks. Future research should establish a multi-scale nested threshold zoning system to achieve comprehensive control across the entire chain – from urban GI planning and management to neighborhood design guidelines (D. LI et al. 2023). Second, current cross-section-based "spatial thresholds" cannot capture the dynamics of "temporal thresholds"; long-term data are needed for dynamic early-warning models. Third, thresholds are applicable to Harbin and require local calibration for other cities. The zoning framework and thresholds should be regularly reviewed and updated, taking into account climate change trends and reflecting progress in urban development.

5 Conclusion

This study established an "assessment-identification-zoning-application" threshold-driven management framework. It reveals the nonlinear mechanisms dominated by climatic background factors and their synergy with anthropogenic factors in shaping ecological security patterns in cold-region legacy industrial cities, quantifies ecological security thresholds to enable quantitative early warning, and proposes six spatial management zones. These findings provide quantitative control baselines and GI configuration guidelines for territorial spatial planning in cold-region legacy industrial cities. Future efforts should further develop climate-resilient sustainable urban zoning frameworks to achieve the goal of resilient development in these cities.

Acknowledgments

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Quantifying the Effects of Tree Species, Time, and Street Type on Visible Greenery in Urban Streets

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Abstract: Visible greenery plays an important role in improving the visual appeal and liveability of urban streets. Planting street trees is one of the most effective ways to increase residents' daily perception of urban greenery. However, previous studies have often treated visible greenery as a static condition, failing to capture how its visual benefits evolve with tree growth, species differences, and variations in street spatial form. This study adopts a simulation approach to quantitatively assess the dynamics of visible greenery provision (VGP) in urban streets. Two typical street types and two common urban tree species in Munich were selected, with tree crown geometries derived from municipal tree inventory data. A total of 280 planting scenarios were simulated to explore how tree species, planting density, and street type jointly influence VGP over time. The results indicate that street type has a significant impact on VGP development, and a nonlinear relationship exists between planting density and visible greenery. The results suggest that an optimal planting density may exist for specific combinations of tree species and street type. The findings provide valuable insights into effective tree-planting strategies for enhancing long-term visible greenery in urban streets.

Keywords: Urban tree planting, urban street, visible greenery, canopy growth dynamics, visibility simulation

1 Introduction

The positive impact of greenery on human well-being is well-documented (LU 2019, ULRICH et al. 1991). Visible greenery, the greenery within the human view field, plays an important role in shaping the quality of urban streets and promoting human health (LARKIN & HYSTAD 2019). Among all sources of visible greenery, street trees are one of the most direct and dynamic forms of everyday contact with nature for city dwellers (ZHU et al. 2022).

Recent studies have highlighted a mismatch between commonly used quantity-based measures of urban greenery and perception-oriented metrics of visible greenery (ORDONEZ et al. 2023). Increasing the number of trees alone does not necessarily improve visible greenery, since excessive planting may cause visual obstruction, spatial crowding, and long-term maintenance challenges (MULLANEY et al. 2015). The contribution of each street tree to visible greenery depends on interacting factors, including tree species, tree arrangement, and the spatial form of the street (CHEN et al. 2015, ZHU et al. 2024). Moreover, this contribution changes over time as the tree canopy grows and interacts spatially with its surroundings. Ignoring such temporal dynamics and contextual factors can lead to a mismatch between the intended design outcomes and the actual visual experience of pedestrians.

Previous studies have quantified visible greenery in urban environments based on street view images (AIKOH et al. 2023). However, these approaches fail to capture the site-specific and dynamic visual benefits provided by individual street trees. Although recent advances in 3D visibility analysis have enabled more detailed simulations of visible greenery in street spaces (CIMBUROVA & BLUMENTRATH 2022), few studies have integrated differences in tree species

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and canopy growth trajectories into visibility evaluations. Furthermore, the long-term relationship between street type and visible greenery provision under different planting densities remains insufficiently understood.

To address these gaps, this study aims to establish a framework for assessing the visible greenery provision (VGP) in urban streets, considering the combined effects of tree species, planting density, street type, and canopy growth over time. This approach emphasizes the importance of linking tree growth dynamics with the visible greenery of the street, offering new insights into tree-planting strategies that enhance long-term benefits.

2 Methodology

2.1 Study Site

This study was conducted in Munich, Germany, focusing on two typical urban street types that represent common spatial forms in the city center. As shown in Figure 1, Street Type I represents a narrow street with a central roadway, parking spaces, and sidewalks on both sides, where the parking spaces serve as potential locations for planting street trees. This type corresponds to a common local street between urban blocks in the city center. Street Type II represents a wider street with potential planting spaces located on the sidewalks, which functions as a key traffic axis in the inner city. Both street types are intensively used in daily urban life but are characterized by a limited availability of visible greenery. Each street segment was defined as 100 m in length, corresponding to the typical block distance between two intersections in the urban grid.

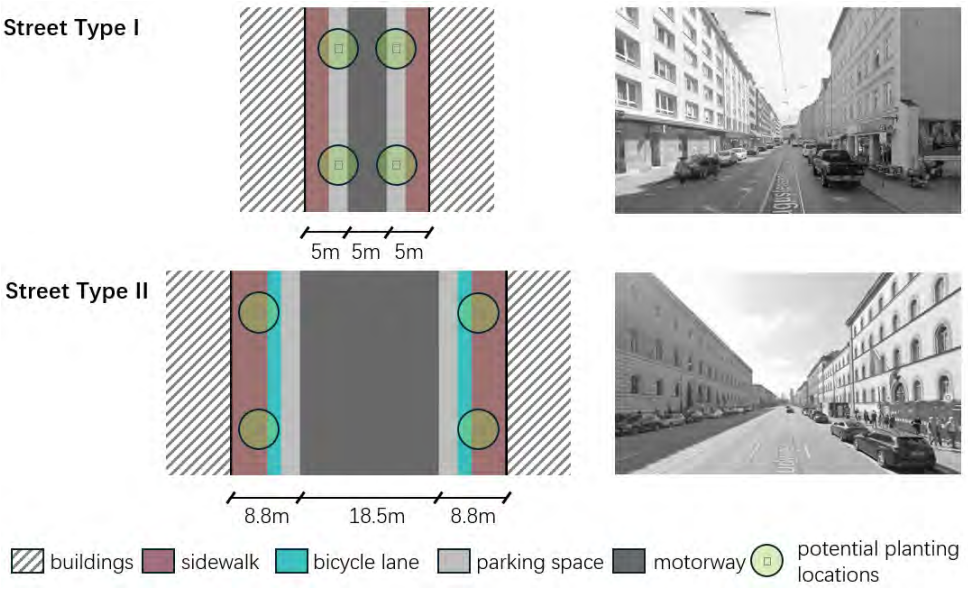

Fig. 1: Two representative street types used in the study, schematic plan views (left) and corresponding street-level images (right)

2.2 Selection of Tree Species and Crown Development Across Growth Stages

This study selected the two widely planted urban tree species, *Tilia cordata* and *Platanus* × *hispanica*, according to the Munich urban tree inventory (RÖTZER et al. 2021). For each species, seven growth stages, from 10 to 70 years, were examined to represent different crown development phases (Fig. 2). The crown shape at each stage was parameterized using average values of tree height, crown length, and crown diameter obtained from the inventory data (RÖTZER et al. 2021).

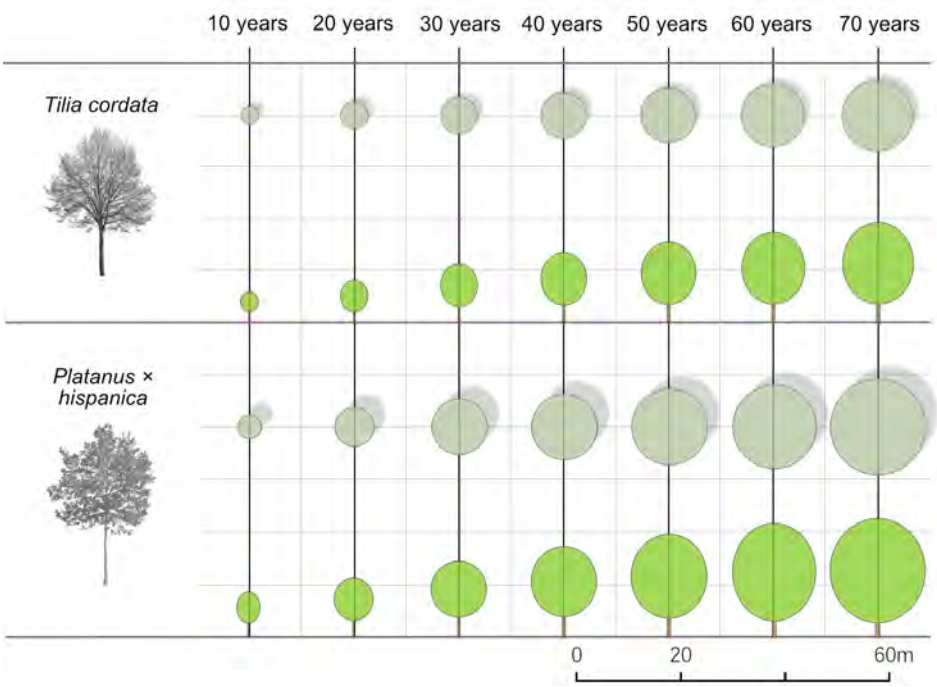

Fig. 2: Crown development of two urban tree species across seven growth stages. For each species, the upper row (light green) shows the crown in plan view, while the lower row (dark green) shows the corresponding crown in elevation view (RÖTZER et al. 2021).

2.3 The Calculation of VGP

The VGP of street trees was calculated using a 3D visibility analysis implemented in Rhinoceros and Grasshopper, with reference to established methods in urban spatial visibility (QI et al. 2022). Observation points were distributed along both sidewalks of each 100 m street segment at 4 m spacing, which serves as the spatial sampling resolution. Each viewpoint was set at a height of 1.6 m to approximate human eye level. From every viewpoint, sightlines were generated uniformly within a 360° horizontal and 120° vertical field of view (PANERO & ZELNIK 1979). The maximum sightline length was 100 m, and rays were cast at 5° angular intervals. Each sightline was tested for intersection with three element classes:

trees, buildings, and ground. For each viewpoint, the number of tree-intersecting sightlines (ST_i) was divided by the total sightlines (SW). The VGP for a street segment was computed as the sum of all viewpoints:

$$\mathrm{VGP} = \sum_{i}^{n} ST_i / SW$$

where n is the number of viewpoints, ST_i is the count of sightlines intersecting trees at viewpoint i, and SW is the total sightlines emitted from viewpoint i.

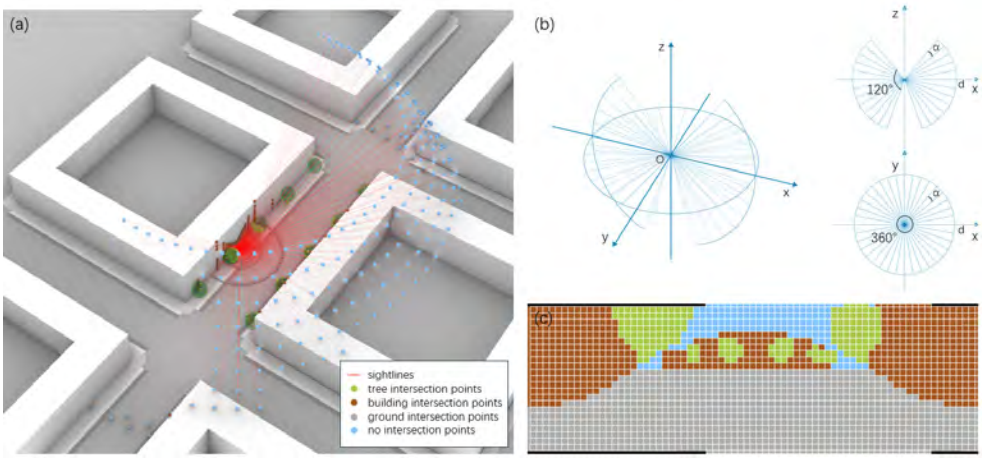

Fig. 3: Illustration of the calculation process for VGP: (a) Generation of sightlines and classification of intersection points with trees, buildings, and the ground, (b) Definition of viewing angles in horizontal (360°) and vertical (120°) directions, (c) Projection of visible elements on a viewing plane, where green, brown, grey, and blue cells represent trees, buildings, ground, and sky

2.4 Planting Scenario Setting and Data Analysis

To systematically evaluate the effects of tree species, street type, and growth stage on VGP, a series of planting scenarios were established by varying three key factors. Street trees were arranged in a double-sided, equally spaced configuration, with the number of planted trees set to 4, 6, 8, 10, 12, 14, 16, 18, 20, and 22, resulting in ten distinct planting arrangements. Combined with two street types, two tree species, and seven growth stages, a total of 280 scenarios were simulated.

The resulting VGP values were analyzed using multiple visualization approaches. Spatial mapping was employed to illustrate the relative value and spatial variation of VGP along the sidewalks under different planting quantities. In addition, line charts were used to depict how total and per-tree VGP changed with tree age and planting density in the two street types. These analyses together reveal both the overall visible greenery dynamics and the differences in average individual tree contributions.

3 Results

3.1 Changes in VGP with Increasing Number of Planted Trees

Figure 4 presents the spatial mapping of VGP along the sidewalks of Street Type II for 30-year-old trees. With the increase in tree numbers, the overall visibility of greenery was enhanced, becoming more continuous along the walking path. However, clear differences were observed between the two species. When n = 8, *Tilia cordata* presented a relatively regular VGP pattern that corresponds closely to the tree spacing. In contrast, *Platanus* × *hispanica* exhibited notably lower VGP values at the ends of the street segment, suggesting that its wider crowns provided uneven visual coverage near the boundaries. When n = 12, the locations of maximum VGP differed between species: for *Tilia cordata*, the highest visibility values appeared directly beneath or near the tree crowns, while for *Platanus* × *hispanica*, the highest values occurred in the uncovered areas between adjacent crowns.

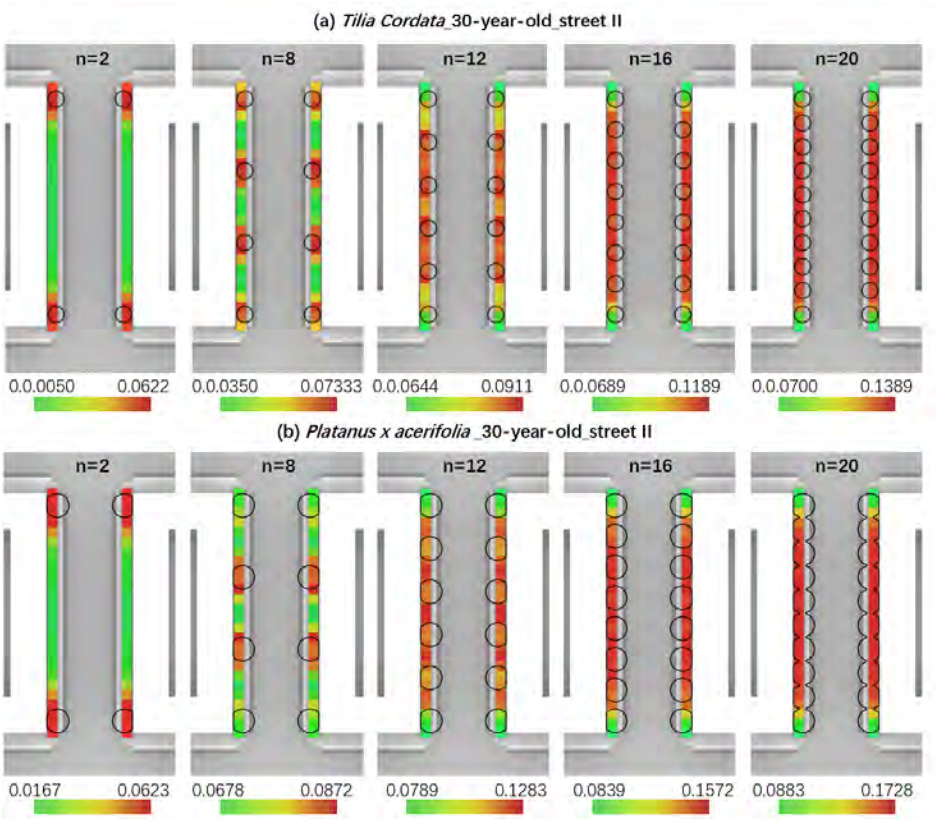

Fig. 4: Spatial distribution of VGP along sidewalks under different tree quantities for 30-year-old trees in Street Type II

Figure 5 shows the relationship between the number of planted trees and their VGP in two street types. As shown in Figure 5a, the total VGP of both *Tilia cordata* and *Platanus* × *hispanica* increased with tree number, though the rate of increase gradually slowed at higher densities. Figure 5b revealed a nonlinear trend in the average VGP per tree: it first increased with tree number, then stabilized, and began to decline once the tree number exceeded approximately 10 per 100 m street segment. This pattern indicated a threshold effect, where additional trees no longer enhanced but rather reduced the individual visibility contribution due to canopy overlap and visual occlusion.

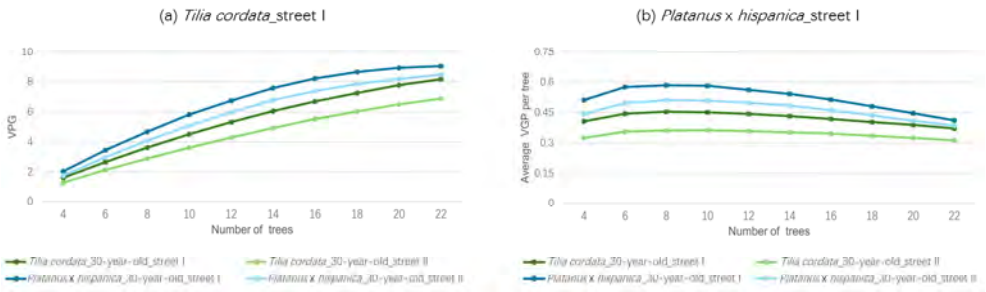

Fig. 5: Total and per-tree VGP under different tree quantities: (a) Total VGP of *Tilia cordata* and *Platanus* × *hispanica* along Street Type I with increasing numbers of planted trees (b) Average VGP per tree under the same conditions

3.2 Effects of Street Type and Planting Density on the Temporal Dynamics of VGP

The results demonstrated that the street type had a strong influence on the VGP of trees. As the trees aged, those in Street Type I showed a clear slowdown in VGP increase, whereas those in Street Type II maintained a more continuous upward trend. When the number of trees per 100 m street segment exceeded 12, the differences in total VGP among planting quantities became much smaller, indicating a saturation effect (Fig. 6). From the perspective of individual trees, the configuration with n = 8 consistently achieved the highest average VGP per tree across all growth stages (Fig. 7). Moreover, when n = 4, the rate of VGP increase with age was most pronounced. Street Type II exhibited a faster increase in per-tree VGP with age compared to Street Type I.

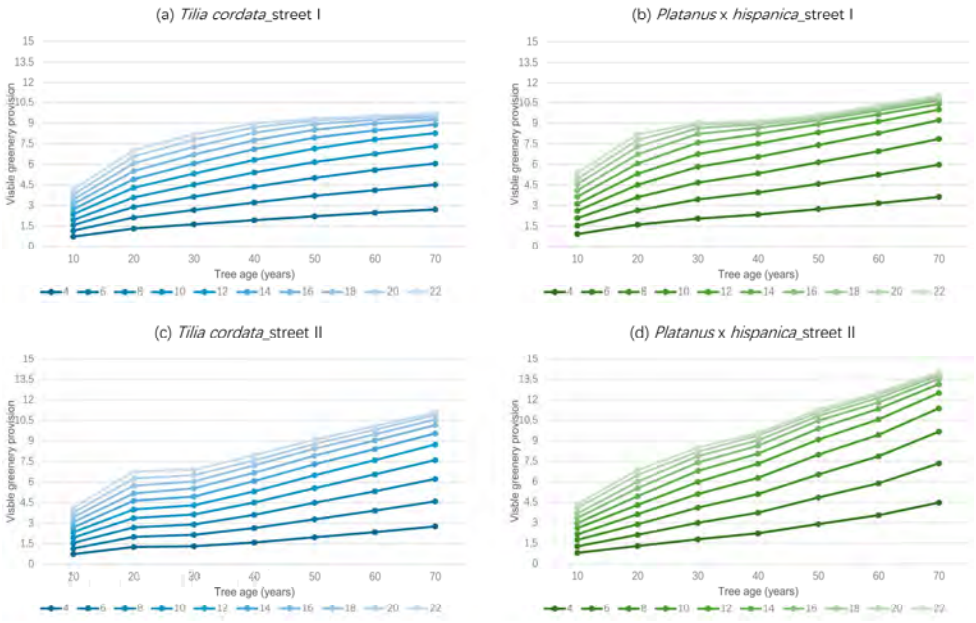

Fig. 6: Changes in total VGP across tree growth stages under different planting quantities and street types

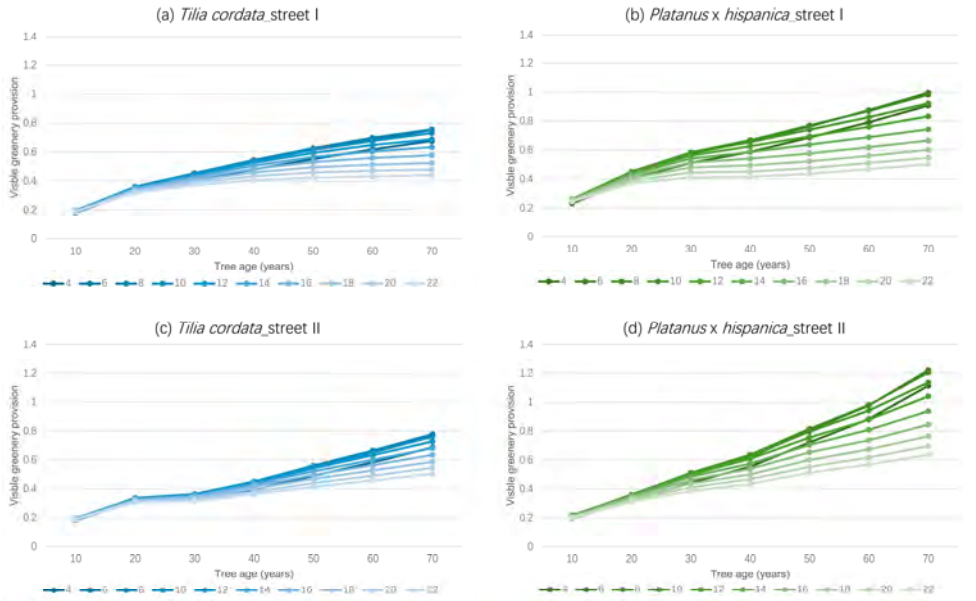

Fig. 7: Changes in average VGP per tree across tree growth stages under different planting quantities and street types

4 Discussion

This study explored how tree species, planting density, and street type jointly influenced the VGP of urban street trees over time. The results indicate that street type plays a decisive role: in narrow streets, VGP growth slows with tree age, whereas in wider streets it continues to increase, likely due to greater openness and visibility. A nonlinear relationship was found between planting density and visual benefit. When the number of trees exceeded around 12 within a 100 m street segment, total VGP gains became marginal, while the average per-tree VGP peaked at 8 trees across all growth stages. These findings suggest that for specific street types and species combinations, an optimal planting density may exist that maximizes visual benefits.

The proposed simulation framework can be integrated with generative design approaches to create tree-planting configurations for particular urban streets and evaluate their short- and long-term visible greenery performance. Within a multi-objective optimization framework, VGP can be assessed alongside other ecosystem services provided by street trees, such as shade provision (ZHANG & LUDWIG 2025), air pollution mitigation (VAILSHERY et al. 2013), and runoff reduction (BERLAND et al. 2017). Trade-offs may arise between maximizing VGP and optimizing other services. For example, species with visually expansive crowns may enhance visible greenery but could reduce daylight penetration into adjacent buildings or increase maintenance demands. The relative weighting of objectives should be defined within the specific planning context, potentially through policy priorities, expert evaluation, or stakeholder-based decision processes.

Several limitations of this study should be acknowledged. First, the analysis relied on simplified geometric simulations in which tree crowns were represented by idealized shapes. Such representations inevitably differ from the actual forms of street tree canopies, whose growth is influenced by local site conditions, climatic variability, and competition among trees (YAZDI et al. 2024). Second, the effects of seasonal pruning and tree mortality on the development of the canopy were not accounted for. Future studies could build on the proposed framework by incorporating seasonal pruning and differentiated tree growth models that reflect varying growth trajectories under different management conditions (SHU et al. 2024), allowing the simulation of design scenarios across multiple time periods. Third, this study only examined street trees arranged in a double-sided, equally spaced configuration; consequently, the findings do not encompass the full range of possible planting patterns. In practice, tree planting in existing urban streets is often constrained by underground infrastructure, aboveground utilities, and other regulations, making uniform spacing difficult to achieve. However, the proposed framework can accommodate predefined or irregular planting locations by adjusting spatial input parameters, enabling the evaluation of feasible planting alternatives under real constraints. Moreover, future research could further validate the proposed approach by comparing simulation results with observations derived from real street-level imagery.

Acknowledgements

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Geospatial Analytics of Food Miles from Bangkok's Peri-Urban Agricultural Landscape to Enhance Urban Food System Resilience

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Abstract: Rapid urbanisation in Southeast Asia has weakened spatial linkages between peri-urban food production and urban consumption. Although food miles are widely used as environmental indicators, their application in spatial planning remains limited. This study operationalises the Weighted Average Source Distance (WASD) within a reproducible geospatial workflow to analyse distance-quantity relationships in peri-urban food distribution. Using a 2024 post-pandemic survey dataset from 48 farms and 261 vegetable-flow routes in Thawi Watthana District, Bangkok, the analysis reveals a distribution system characterised by long-distance transport: 75% of production occurs beyond a 30 km radius, accounting for 80% of the overall WASD (38.5 km), despite the geographic proximity of production to urban demand. To support planning-oriented interpretation, distribution flows are analytically structured into distance-based categories representing near-city (≤15 km), mid-range (15-30 km), and metropolitan-scale (>30 km) supply connections. This distance-tiered spatial analysis demonstrates how transport intensity is unevenly concentrated across space and highlights structural mismatches between geographic proximity and prevailing distribution practices. Validation in Bangkok suggests that this geospatial framework can support spatial diagnosis of food-system vulnerabilities in other rapidly urbanising metropolitan regions.

Keywords: Geospatial analytics, food miles, peri-urban agriculture, resilience planning, Bangkok

1 Introduction

Contemporary metropolitan areas face increasing vulnerability in their food systems as urban expansion extends supply chains and heightens reliance on distant logistics networks (ABU HATAB et al. 2019). Food miles – the distance food travels from production to consumption – are often used as indicators of environmental impact and system resilience (WEBER & MATTHEWS 2008). Although peri-urban agriculture continues at metropolitan outskirts worldwide, the ways in which geographically nearby production areas are practically integrated into urban food distribution systems remain inconsistent and poorly understood (TENDALL et al. 2015). In rapidly urbanising settings, geographic proximity does not necessarily result in short-distance supply-chain links, raising questions about how food distribution is organised spatially in practice.

Southeast Asian megacities exemplify these challenges at an accelerated scale. Urbanisation rates exceeding 2.5% annually have driven rapid peri-urban land conversion, yet agricultural production systems continue to operate within transitional zones surrounding metropolitan cores (DRESCHER et al. 2015). Cities such as Jakarta, Manila, and Bangkok maintain substantial vegetable production within 30-50 km of urban centres, but how produce from these areas is distributed across metropolitan markets – particularly at the scale of individual production

districts – remains underexplored (MULYA et al. 2024, PRIBADI & PAULEIT 2015). Despite growing interest in food-mile analysis, spatially explicit studies that translate distance-based metrics into planning-relevant evidence remain limited in high-density Asian megacities (SCHREIBER et al. 2021).

Bangkok Metropolis, with approximately 11 million residents within an administrative area of 1,500 km² (DANGELSÈR 2022), represents one of Southeast Asia's largest high-density urban systems. Despite urbanisation averaging 1.5% annually over recent decades (MACROTRENDS 2024), peri-urban districts continue to host active vegetable production, with designated agricultural zones located within approximately 15-30 km of the urban core. However, the actual distribution pathways through which vegetables produced in these districts reach metropolitan markets have not been systematically documented at the district scale. In particular, it remains unclear how far vegetables produced in western peri-urban districts are transported, how distribution distances differ across market types, and how transported quantities are allocated between near- and distant-supply routes.

While vegetable distribution may extend beyond Bangkok's administrative boundary, the empirical analysis in this study focuses on production originating within Bangkok Metropolis, using Thawi Watthana District as a district-scale case to examine metropolitan food distribution patterns.

Previous research has offered valuable insights into Bangkok's food system, but with differing analytical focuses. Drescher et al. (2015) mapped vegetable flows across Greater Bangkok, highlighting the dominance of wholesale-oriented distribution networks at a metropolitan level. Menakanit et al. (2022) examined land fragmentation and agricultural land loss in Thawi Watthana District, noting pressures on peri-urban production capacity. However, a gap persists between metropolitan-scale foodshed mapping and district-scale analyses that track the actual distribution of agricultural products from specific production areas, including quantities and distances. This gap is especially relevant in the post-COVID-19 context, where food distribution structures may have experienced significant adjustments.

In food planning and urban studies, local food systems and peri-urban agriculture are increasingly understood through functional and relational links among production areas, distribution infrastructure, and urban consumption zones, rather than through fixed, territorially bounded market definitions. Within this body of literature, distance is commonly used as an analytical and operational variable to examine how food supply chains are spatially organised and how transport intensity is spread across space. Building on this conceptual approach, our study employs distance ranges as planning-focused analytical tools to explore how institutionalised distribution pathways shape food distribution patterns originating from a single peri-urban production district. Importantly, these distance ranges are not intended to set normative definitions of "local" or "regional" food systems, but to identify spatial mismatches between geographic proximity and actual distribution practices.

This study addresses these gaps by operationalising the Weighted Average Source Distance (WASD) as a planning-oriented geospatial metric within a distance-based analytical framework (PETERS 2022, WEBER & MATTHEWS 2008). Using post-pandemic field survey data from peri-urban vegetable farms in Thawi Watthana District, the research contributes through: (1) empirical documentation of where vegetables produced in a single Bangkok district are distributed and in what quantities, (2) analysis of distance-quantity relationships using distance-tiered WASD analysis, and (3) development of a planning-focused spatial

framework that translates empirical distance-flow metrics into practical insights for metropolitan food system planning.

2 Study Area and Data

Thawi Watthana District is situated on Bangkok's western metropolitan fringe (13.77° N, 100.34° E), covering roughly 62 km² of mixed peri-urban farmland and low-density residential areas. Despite continuous urbanisation, the district remains one of Bangkok's main vegetable production zones (MENAKANIT et al. 2022).

Field surveys conducted between March and May 2024 identified 48 active vegetable farms and documented 261 production-flow routes linking farms to market destinations. Market destinations were classified into two categories based on operational features observed during fieldwork: (1) wholesale markets, defined as large-scale centralised distribution hubs serving multiple retailers, and (2) retail markets, including fresh markets, institutional buyers (e. g., schools and hospitals), and direct-to-consumer outlets. This binary classification reflects Bangkok's prevailing distribution structure and offers an analytical basis for comparing different types of supply-chain pathways.

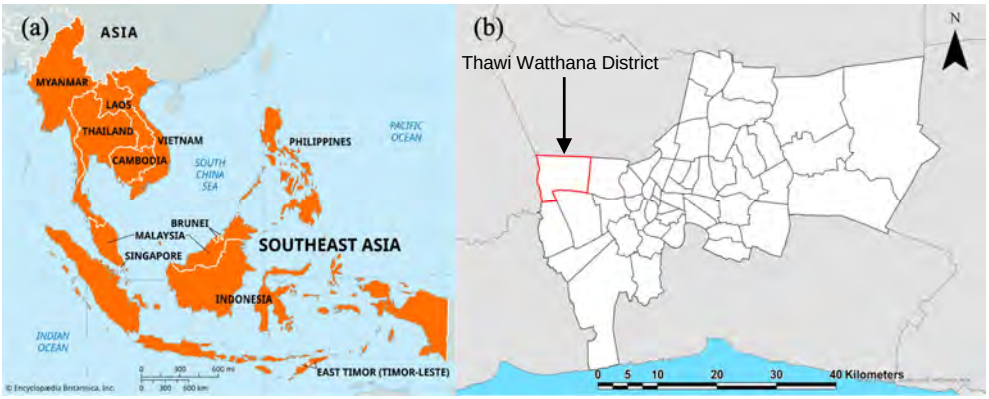

Fig. 1: Study area within Bangkok Metropolis: (a) regional context in Southeast Asia, (b) administrative boundary of Bangkok, highlighting Thawi Watthana District as the focal peri-urban production area

Farm locations were recorded using GPS, and information on shipment quantities and market destinations was collected through structured interviews with farmers and vendors. Data validation employed multiple procedures, including cross-checking reported quantities against market receipts (12 vendors; 91% concordance), verifying destination locations using GPS and satellite imagery (±10 m accuracy), and confirming production capacity through plot-size calculations. These procedures follow established approaches in foodshed and food-flow mapping studies (PETERS et al. 2008, SCHREIBER et al. 2021). Shipment quantities were annualised based on reported cropping calendars and delivery frequencies. The resulting dataset provides spatially explicit documentation of peri-urban vegetable distribution originating from Thawi Watthana District and enables comparison with earlier metropolitan-scale studies (DRESCHER et al. 2015).

3 Analysis Methods

Data on vegetable production quantities (kg/year) and market destinations for 261 flows from 48 farms were collected through field surveys conducted between March and May 2024. Food-mile distances were calculated using the Weighted Average Source Distance (WASD) model (PETERS 2022, WEBER & MATTHEWS 2008):

$$WASD = \Sigma (q_i \times d_i) / \Sigma q_i$$

where q_i represents shipment quantity (kg/year) and d_i the network distance (km) from farm i to its market destination. Network distances were calculated in QGIS 3.28 using Dijkstra's algorithm on OpenStreetMap road networks, thereby reflecting actual travel routes rather than straight-line distances (GALZKI et al. 2014). Validation against Google Maps routing for 30 randomly selected origin-destination pairs showed a median deviation of 4.3% ($r = 0.987$), indicating high reliability of the network-based distance dataset.

To organise the spatial analysis, distance-based analytical categories (≤15 km, 15-30 km, and >30 km) were used as planning-oriented diagnostic tools. These ranges were not meant to establish fixed or normative market boundaries but to enable systematic comparison of proximity-based and extended distribution pathways within Bangkok's metropolitan area. Distance-tiered WASD analysis was used to assess retained production quantities, category-specific WASD values, and the contribution of each distance tier to overall transport intensity, thereby supporting evaluation of distance-quantity trade-offs relevant to spatial planning. These distance-based analytical categories represent observed routing configurations rather than hypothetical intervention scenarios.

4 Results

Analysis of 261 vegetable flows from 48 farms in Thawi Watthana District reveals a predominantly long-distance distribution pattern when evaluated across distance-based analytical categories. The overall Weighted Average Source Distance (WASD) was 38.5 km, with a median of 44.6 km, indicating a heavy reliance on extensive logistics routes despite the proximity of production areas to urban demand. Only 17% of total vegetable production was distributed within 15 km, and 25% within 30 km. Conversely, 75% of production was transported beyond 30 km, accounting for 80% of the total WASD. Table 1 summarises the evaluation of distance-tiered categories in terms of retained production quantities, category-specific WASD values, and their relative contribution to overall transport intensity. Although the WASD reflects a quantity-weighted average, many wholesale routes extended well beyond 60 km. Together, these results demonstrate how distance-tiered analysis enables systematic evaluation of distance-quantity relationships within an existing metropolitan food distribution system.

Table 1: Thawi Watthana's vegetable distribution: distance ranges and WASD analysis

Distance Range (km)	Production Quantity (%)	Production Quantity (kg/year)	Distance-Tier WASD (km)	Contribution to Overall WASD (%)
0-15	17	~65,000	8.2	8
15-30	8	~30,000	22.8	12
>30	75	~287,000	43.9	80
Total	**100**	**~382,000**	**38.5**	**100**

Disaggregation by distance-based category reveals contrasting contributions to overall transport intensity. Flows exceeding 30 km account for 75% of the production quantity and contribute 80% of the total WASD, with a category-specific WASD of 43.9 km. In contrast, flows within 15 km account for 17% of production but only 8% of total WASD, with a category-specific WASD of 8.2 km. The intermediate 15-30 km range falls within a transitional category, accounting for 8% of production volume and 12% of overall WASD.

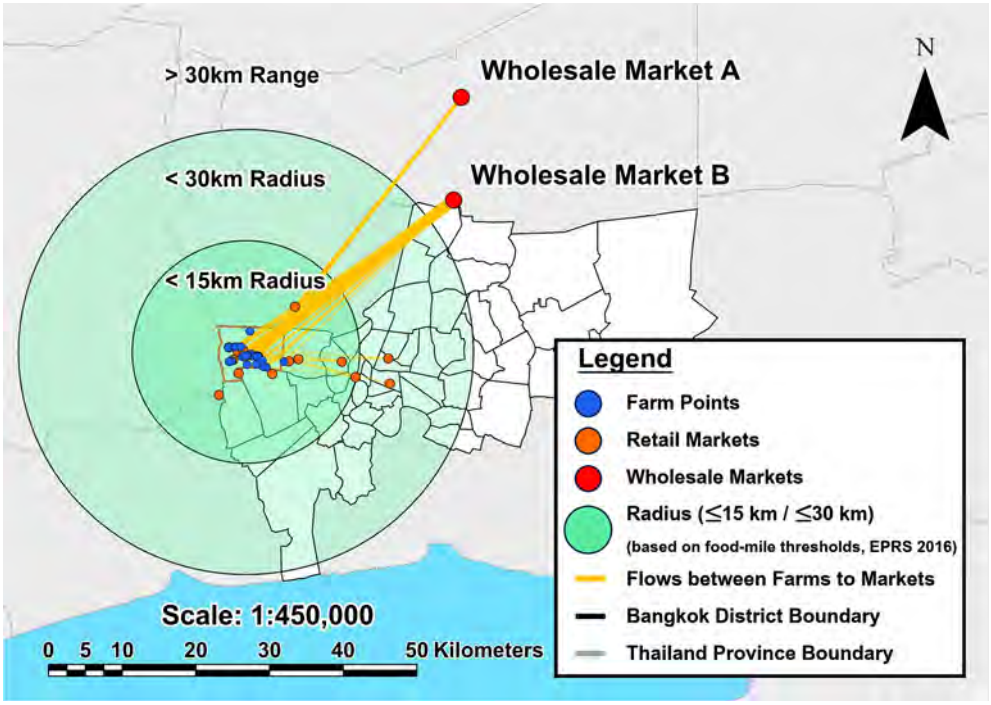

Fig. 2: Foodshed map of vegetable distribution from peri-urban farms in Thawi Watthana District, showing the differences between local retail routes and long-distance wholesale pathways

Spatial analysis of market destinations further clarifies these patterns. Of the 261 documented flows, 198 (76%) terminate at wholesale markets, which serve as centralised aggregation points located beyond the peri-urban edge of Bangkok Metropolis, relative to Thawi Wat-

thana District. The remaining 63 flows (24%) connect farms directly to retail destinations, including fresh markets, supermarkets, and institutional buyers such as schools and hospitals. These direct retail flows demonstrate significantly shorter transport distances, as illustrated in Figs. 2-3.

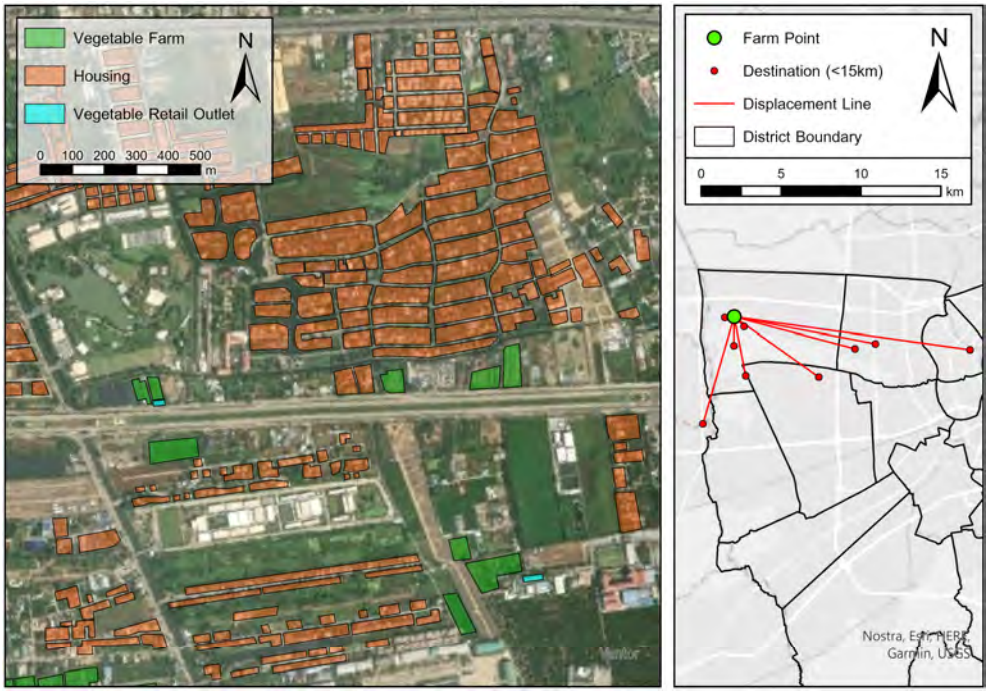

Fig. 3: Spatial organisation of vegetable farms (producers), vegetable retail outlets (distributors), and housing estates (consumers) in an area of Thawi Watthana District

Fig. 4: Proximity-based, non-wholesale vegetable distribution in Thawi Watthana District: (a) farm-gate retail outlet serving nearby residential areas, (b) on-site packaging of vegetables for direct local retail distribution

Field observations identify on-farm retail outlets that enable direct distribution to nearby residential communities (Figs. 3-4). These outlets exemplify proximity-based distribution within the study area and provide empirical evidence of alternative non-wholesale distribution routes.

5 Discussions and Outlook

The findings demonstrate the persistence of a wholesale-dependent distribution structure in Bangkok's peri-urban vegetable sector, despite the geographic proximity of production areas to metropolitan demand. These findings emerge from a diagnostic, distance-tiered evaluation of existing distribution pathways. Although earlier studies identified similar patterns at the metropolitan scale (DRESCHER et al. 2015), this study confirms that such spatial inefficiency endures at the level of a single production district in the post-pandemic context. The results suggest that proximity alone is insufficient to facilitate short-distance food distribution; instead, institutional and logistical arrangements play a crucial role in shaping routing decisions, often favouring long-distance pathways even when shorter options are spatially viable.

A key contribution of this research is reinterpreting distance thresholds as analytical tools rather than normative benchmarks. The use of distance-tiered WASD analysis does not imply that food distribution should occur within specific distances; instead, it demonstrates how different routing configurations concentrate transport activity within particular spatial ranges. In this context, the prominence of long-distance flows emerges as an empirical feature of the current distribution system, emphasising how centralised wholesale infrastructure systematically shapes food flows in ways that bypass geographic proximity.

Methodologically, this study advances beyond simple foodshed mapping by applying WASD within a planning-oriented, analytically structured spatial framework. Using network-based distances that reflect the actual road infrastructure, the analysis enables evaluation of different distribution arrangements and their spatial impacts. This approach enhances the utility of food-mile analysis for landscape architecture and urban planning, where decision-making requires tools that can diagnose spatial organisation and assess potential interventions rather than merely documenting current conditions. Here, the analytical framework is used to diagnose how current routing configurations distribute transport intensity across space, rather than to simulate alternative distribution scenarios or planning interventions.

From a planning perspective, the findings highlight the significance of peri-urban agricultural land as a vital part of food infrastructure. Field observations show that proximity-based retail pathways already exist as an adaptation toward urbanising areas, supported by institutional programmes that enable direct farm-to-consumer distribution (ZASADA 2011). Although these pathways currently account for a small share of total flows, distance-tiered modelling indicates that a modest expansion could yield notable reductions in overall transport intensity without affecting production capacity. This emphasises the potential of spatial planning and design interventions – such as improving access to farm-gate retail and incorporating local markets into neighbourhood contexts – to support existing wholesale systems and enhance system resilience. In this context, "design interventions" refer to adjustments in spatial organisation and distribution logic – such as connectivity, access, and routing.

Several limitations should be acknowledged. The analysis is based on data from a single season and a single peri-urban district, which may not reflect seasonal variation or patterns

in other parts of Bangkok. Economic aspects, including production costs, retail profitability, and consumer demand, were beyond the scope of this study and require further exploration. Additionally, the analytical framework represents conceptual modelling rather than implemented interventions, emphasising the need for future pilot projects.

Future research could expand this framework through comparative studies of Southeast Asian megacities, assessments of ecological footprints for different distance-tiered distribution systems, and analyses of institutional procurement mechanisms that facilitate sourcing locally produced food. Overall, this study highlights how geospatial analysis can bridge the gap between measuring food miles and spatial planning by converting distance-flow metrics into insights relevant for planning. In rapidly urbanising regions facing growing supply-chain uncertainties, strengthening the functional integration of peri-urban agriculture offers a practical spatial strategy for improving metropolitan food-system resilience.

6 Conclusions

This study operationalised WASD as a planning-oriented metric through distance-tiered geospatial modelling. Methodologically, the research validated distance thresholds (15/30 km) within Bangkok's metropolitan area and demonstrated how food-mile calculations can inform spatial planning frameworks. The reproducible digital workflow – from network analysis to distance-tier testing – offers a transferable approach for foodshed assessment in rapidly urbanising Southeast Asian contexts.

Empirically, analysis of 261 flows from 48 farms revealed Bangkok's distribution paradox: 75% of peri-urban produce travels beyond 30 km (WASD: 38.5 km) despite being close to metropolitan demand. Compared with the 2013 baseline data, the 2024 data show a 9% increase, indicating that spatial proximity alone does not ensure local distribution without intentional planning. This structural reliance on distant wholesale networks reflects patterns observed across Southeast Asian megacities.

The distance-quantity relationships identified in the analysis highlight spatial distinctions relevant to planning among near-city production (≤15 km), mid-range distribution pathways (15-30 km), and metropolitan-scale supply connections (>30 km). These findings offer an analytical foundation for future planning rather than prescriptive spatial solutions. Regional validation through functioning short-distance models in Bangkok, Thailand, and neighbouring countries confirms the framework's applicability to Jakarta, Manila, Hanoi, and other urbanising regions. Although these interventions remain conceptual, the methodology shows that rigorous geospatial analytics can convert food-mile metrics into evidence-based planning strategies to address food-system vulnerability in Southeast Asia's rapidly urbanising megacities.

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Disclaimer

AI tools (Claude, Anthropic, and ChatGPT) were used solely for English-language assistance, including editing, grammar checking, and proofreading. All research design, data collection, fieldwork, geospatial analysis, interpretation of results, and planning proposals were independently developed and carried out by the research team.

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Shanshui-Informed Digital Rural Planning: Modular Aesthetic-Spatial Mapping with GIS Ecological Analytics

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Abstract: Under rapid urbanization, rural planning in China is often driven by functional efficiency, contributing to ecological fragmentation and landscape homogenization. This paper proposes a modular digital planning framework coupling quantified *shanshui* (Chinese landscape aesthetics) parameters with GIS-based ecological analytics. Traditional landscape paintings are treated as visual proxies for cultural spatial cognition. Computer vision extracts spatial-organizational principles, formalized as an aesthetic-spatial mapping matrix translating compositional rules into computable ecological constraints and spatial weights. The framework guides the generation of ecological, productive, residential, and cultural modules. A case study in Wufeng Village demonstrates improved ecological performance, landscape-visual quality, and service accessibility relative to a baseline scenario, indicating a reproducible pathway for embedding cultural principles as generative rules in performance-driven planning.

Keywords: Aesthetic-spatial mapping,GIS ecological analytics, modular design, digital rural planning, shanshui

1 Introduction

1.1 Research Background and Problem

Rapid urbanization in China, driven by functional efficiency, has alienated human-land relations and fragmented landscape structures. As spatial production erodes local symbols and meanings (LEFEBVRE 1991), standardized construction leads to pervasive homogenization, reducing villages to land-use quotas rather than carriers of collective memory. Addressing this, this paper draws on *Tian-Ren-He-Yi* as a holistic worldview. We adopt a "five-in-one" model integrating ecological, economic, cultural, technological, and aesthetic dimensions (YAO et al. 2018). This perspective aligns with the nature-humanities-technology eco-design framework (WANG & LUO 2018) and *shanshui*-city symbiosis (ZHANG & WANG 2018), framing *shanshui* as a cultural-spatial paradigm to coordinate topography, water systems, and settlement forms.

1.2 Research Gaps and Objectives

Although digital technologies have become standard in contemporary landscape and rural planning, they still face methodological bottlenecks when dealing with culturally complex landscapes. On one side, prevailing digital tools prioritize quantitative modeling of biophysical processes and functional indicators, offering limited means to engage cultural semantics such as *yijing* (artistic conception); this functionalist bias can further intensify cross-regional morphological homogenization. On the other side, culturally oriented planning studies emphasize continuity of cultural context and place identity (WANG 2019, WANG 2021, WU 2024), yet often remain at the level of qualitative strategies or superficial symbol-making,

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lacking an operational pathway to couple spatial design decisions with ecological-physical processes in a systematic, quantitative manner.

Addressing this dual gap, this paper develops a modular digital planning framework jointly constrained by cultural rules and ecological indicators. By analyzing the spatial grammar embedded in Chinese painting and translating it into GIS-recognizable parameters, the framework enables the coordinated advancement of ecological restoration and cultural regeneration in rural landscape space through performance-grounded modeling and computation.

2 From Shanshui Philosophy to Computable Parameters

This study translates the holistic ecological ethic of *Tian-Ren-He-Yi* (Harmony between Man and Nature) into operational spatial language (YU 1996). We adopt *shanshui* as a spatial-organizational paradigm coordinating habitation with natural systems (QIAN 1993, WU & CAO 2022), utilizing traditional landscape paintings as "cognitive maps" that provide implicit, computable rules for 3D spatial arrangement (ZONG 1986, WU 2023).

To bridge cultural translation and digital operation, we draw on Ledderose's (2000) concept of modularization in Chinese art. Recent studies confirm this logic applies to *shanshui* paintings, where finite elements and combinatorial rules construct complex spaces. By treating pictorial elements as standard components and compositional principles as generative algorithms, we establish a structural isomorphism between *shanshui* aesthetics and parametric design. This justifies decomposing fluid cultural expressions into measurable spatial parameters for subsequent GIS quantification (Tab. 1).

Table 1: Operational Definitions of Core Aesthetic Concepts

Aesthetic Concept	**Cultural/Spatial Meaning**	**Measurable Dimensions / Spatial Operations**
Six Distances	A compositional principle for constructing multi-dimensional spatial experience (e. g., high, deep, and level distance).	GIS viewshed analysis; terrain relief/roughness; view-corridor width; building height control.
Gazing-Traveling-Wandering-Dwelling, Sequence	An experiential sequence for an ideal living environment.	Path-network connectivity; density of viewpoints; 10-minute service-area coverage; residential clustering and layout.
Liubai / Void	Rhythmic flow (qi resonance), interplay of void and solid, and spatial "breathing room."	Width of ecological buffer zones; proportion of non-development land; distance to water edges/riparian zones.
Host-Guest / Hierarchical Correspondence	Visual hierarchy and compositional order.	Elevation contrast (primary vs. secondary peaks); dominance of visual focal points.

3 A Digital Workflow Coupling Aesthetics and Ecology

3.1 Study Area and Data

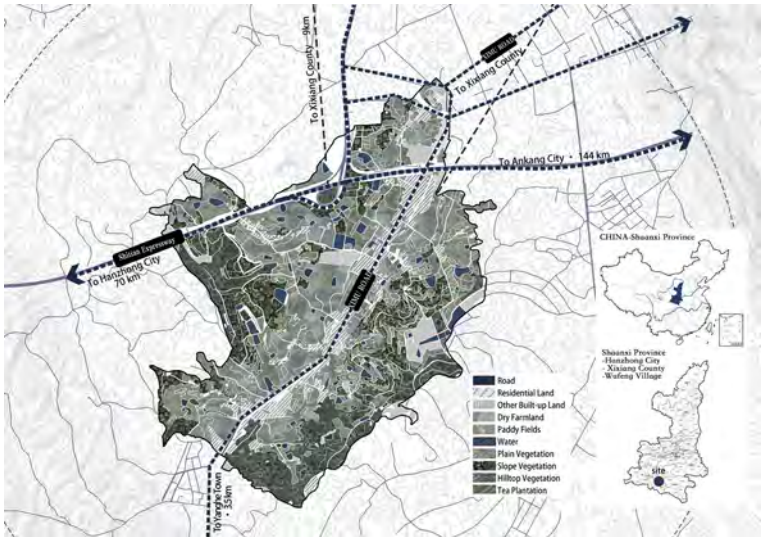

Fig. 1: Site Location and Existing Landscape Conditions

Wufeng Village (Shaanxi Province) was selected because its representative "mountain-water-field-settlement" vertical landform naturally aligns with the nested spatial logic of the "Three Distances" in traditional *shanshui* painting, offering an ideal testing ground against the threat of standardized construction (Fig. 1). Base data includes a 30m DEM, 0.5m satellite imagery, and land-use/hydrological data. The 30m DEM serves as a macro-to-meso topographical baseline. Acknowledging that 30m is too coarse for micro-scale "Six Distances" operations, we calibrated module placements and sightlines using 0.5m imagery and extensive field surveys.

3.2 GIS-Based Ecological Redline Delineation and Suitability Assessment

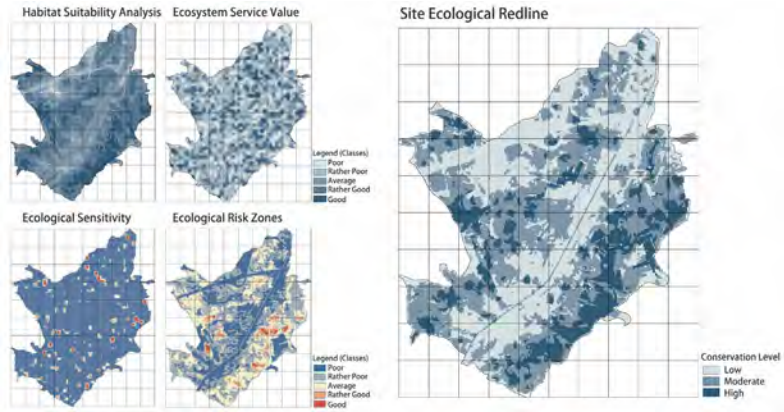

Fig. 2: Workflow and Results for Delineating the Site's Ecological Redline

Using GIS, we construct an ecological redline delineation system centered on multi-dimensional evaluation and weighted overlay. Site ecological attributes are decomposed into four core dimensions and assessed through fine-grained single-factor evaluations (Tab. 2), producing a three-tier protection scheme (low, medium, high). Areas classified as highly sensitive or high-risk are strictly designated as ecological redlines, clarifying differentiated regulatory intensities and providing a precise "*liubai*" (reserved void) base map for subsequent placement of *shanshui*-informed modules.

Table 2: Weighting Scheme for Ecological Redline Delineation

Criterion	Weight	Ecological Rationale
Ecologically Sensitive Areas	0.30	Indicates the sensitivity of the site's baseline ecological conditions
Key Ecological Function Areas	0.10	Represents core supply areas for ecosystem services
Ecological Redline (Vulnerable Zones)	0.40	Vulnerable zones exhibit low ecological stability and therefore require the highest management priority.
No-Development Zones	0.20	Strictly protected areas corresponding to zones of high habitat suitability.

3.3 Digital Extraction and Clustering of Shanshui Aesthetics

To extract *shanshui* modules, we combined machine-vision with art-historical validation (WANG 2021). From a manually compiled corpus of 112 high-resolution image patches from Song-dynasty paintings, we employed the CLIP model to automatically derive high-dimensional numerical feature vectors. This automated step converts abstract visual attributes (e. g., misty rain, steep ridges) into computable mathematical representations for similarity measurement. Following an automated HDBSCAN clustering of these patterns, human experts manually calibrated and semantically labeled the results against the site's baseline to prevent meaningless AI outputs. This hybrid process finalized six tailored pictorial archetypes: Open-Field Hamlet, Hillside Terrace, Forest-Embraced Hills, Construction Reserve, Vibrant Street-Alley, and Forest-and-Spring Ecological Zone.

3.4 The Aesthetic-Spatial Mapping Matrix

To translate abstract pictorial conceptions into implementable spatial schemes, we construct an element-based, hierarchical mapping matrix. Target *shanshui* archetypes are decomposed into specific states of five core elements – mountain, water, forest, settlement, and farmland – and mapped onto combinational GIS conditions across the site. Table 3 summarizes the generation logic for six *shanshui* character zones derived from factor scoring and weighted analysis.

Based on this matrix, GIS is used to validate the site's suitability for the six *shanshui* character zones. Areas with the highest pictorial potential are then selected for each zone to assemble the final planning scheme.

Table 3: A Factor-Scoring and Weight-Based Mapping Matrix for Shanshui Character Zoning

Target Archetype & Zone	Element Characteristics	GIS Weights & Thresholds
A: Open-Field Hamlet Zone *correspondence : Level Distance*	Buildings: scattered; farmland: dense; vegetation: scattered; views: long-range views; slope: flat (0–10°).	Weights: slope 0.30; buildings 0.25; vegetation 0.25. Threshold: slope < 10°.
B: Hillside Terrace with Scattered Dwellings *Correspondence : Deep Distance*	Buildings: moderate; farmland: moderate; vegetation: dense; views: long-range views; slope: moderate (10–25°).	Weights: vegetation 0.50 (highest); farmland 0.30; slope 0.20. Threshold: 10° < slope < 25°.
C: Forest-Embraced Hills *correspondence : High Distance*	Buildings: scattered; vegetation: dense; farmland: scattered; slope: steep (>25°, or 10–25° in some contexts).	Weights: farmland 0.40 (patch protection); vegetation 0.30; slope 0.20. Threshold: slope > 25°.
D: Construction Zone *correspondence : Production*	Buildings: dense; roads: high accessibility; vegetation: scattered; slope: flat (0–10°).	Weights: production buildings 0.40; buildings+roads 0.25; slope 0.10. Threshold: high road-network density.
E: Vibrant Street-Alley Quarter *correspondence : Vibrant Life*	Buildings+roads: dense; services: convenient; vegetation/farmland: scattered; slope: flat (0–10°).	Weights: buildings+roads 0.40; services 0.20; slope 0.20. Threshold: within service-facility catchments.
F: Forest-and-Spring Ecological Zone *correspondence : Void/Seclusion*	Vegetation: dense; water: dense; roads: sparse; ecology: sensitive/vulnerable.	Weights: ecological redline 0.45; vegetation 0.35; roads 0.20. Threshold: within ecological redlines & water-buffer zones.

4 Case Application and Results

The planning proposal is developed across three nested scales: (i) a macro-scale integration of the *shanshui* landscape pattern and functional structure, (ii) a meso-scale landscape-character zoning plan, (iii) a micro-scale design of experiential sequences.

4.1 Macro-Scale: Integration of Landscape Pattern and Functional Network

A viewshed-based framework safeguards long-distance corridors, repositioning the site within the regional urban-rural corridor (Fig. 3). Targeted road connections strengthen visual and ecological linkages to surrounding mountains and waters, establishing the village as a strategic regional ecological node.

4.2 Meso-Scale: Landscape Zoning based on Painting Suitability

We first screen *shanshui* archetypes against field-identified landscape features. Paintings are abstracted into planar diagrams to derive preliminary criteria. Finally, integrating residential, industrial, and ecological factors, we construct a comprehensive evaluation matrix for zoning.

GIS-based multi-character suitability analysis is then conducted to identify optimal locations for each pictorial archetype (Fig. 5). Guided by the spatial organizational logic of *shanshui* painting, the final plan synthesizes an "one axis-two belts-six zones" structure (Fig. 6), ensuring that pictorial conceptions such as level and deep distances are materially projected into the physical landscape (Fig. 7).

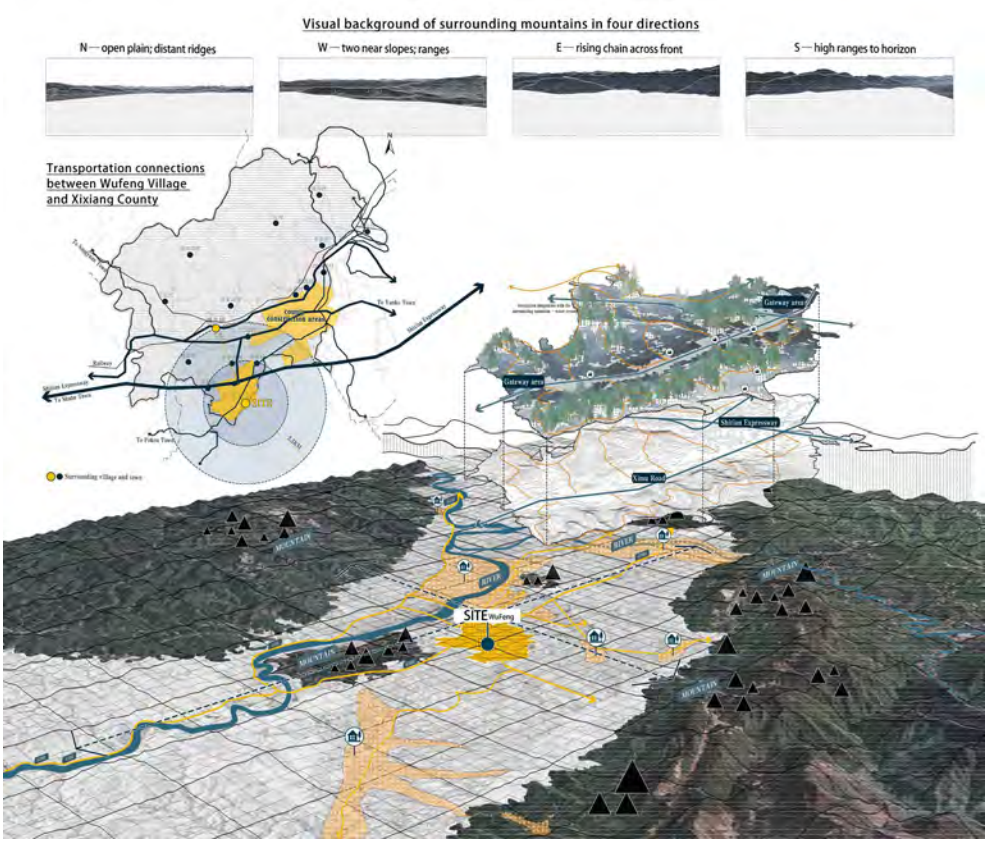

Fig. 3: Surrounding Landscape Pattern and Transportation Plan

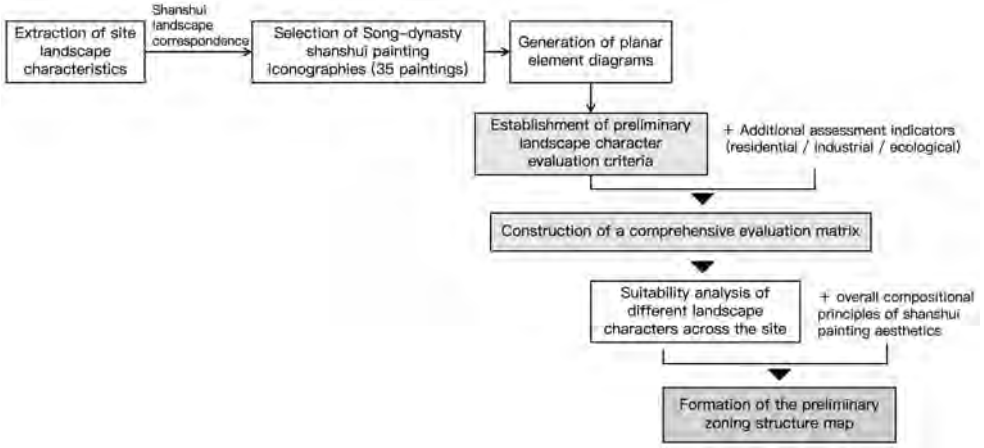

Fig. 4: Technical Workflow for Painting-Informed Zoning

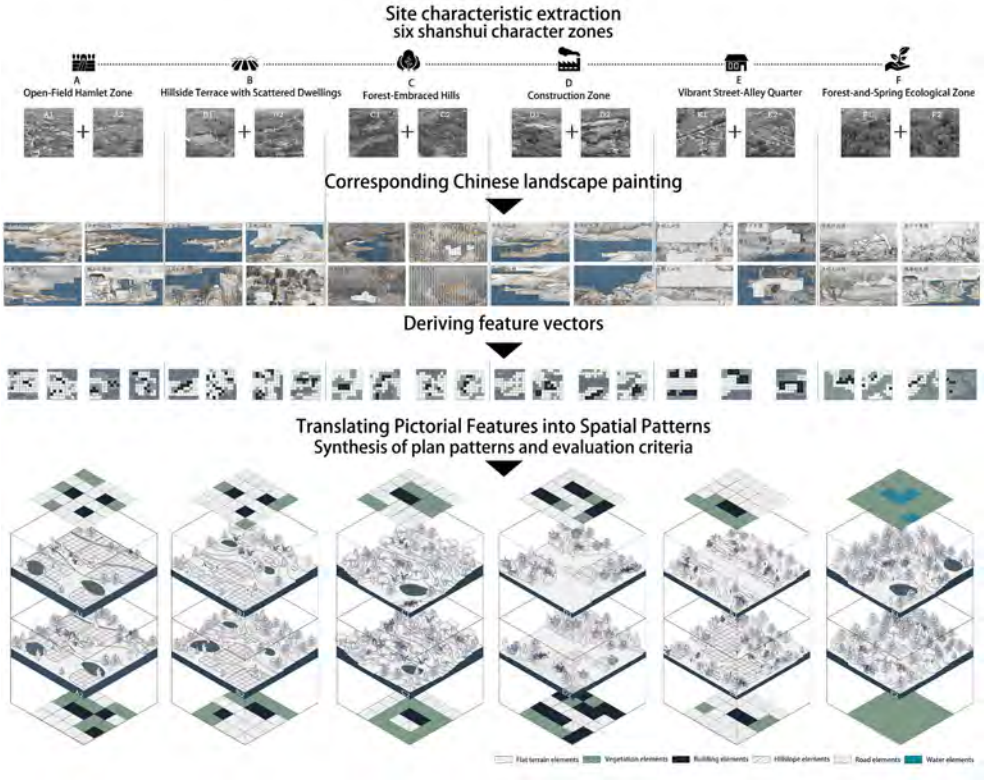

Fig. 5: Spatial Patterns Corresponding to Six *Shanshui* Pictorial Archetypes

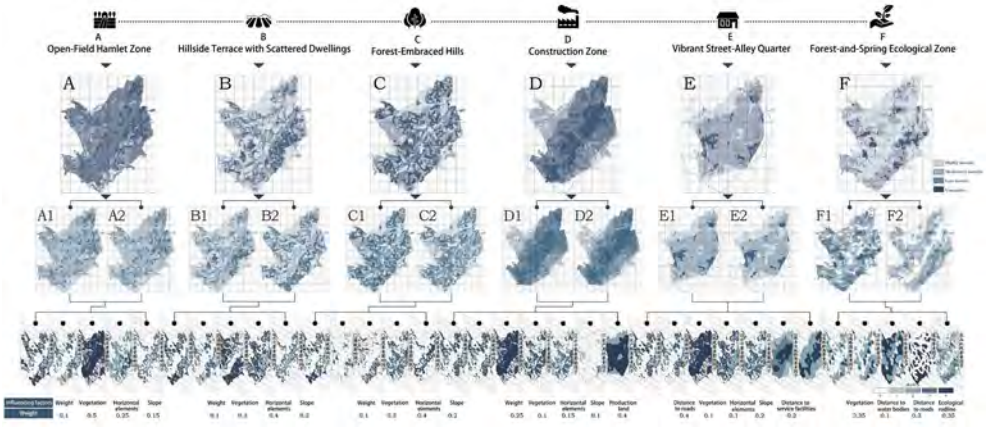

Fig. 6: Suitability Analysis for Six Pictorial Archetypes

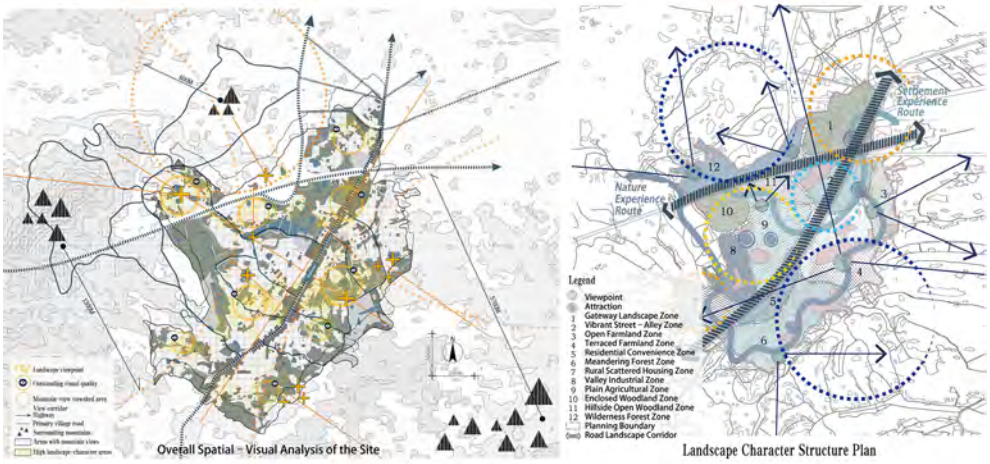

Fig. 7: Structural Diagram of the Landscape Plan：Overall Spatial-Visual Analysis of the Site

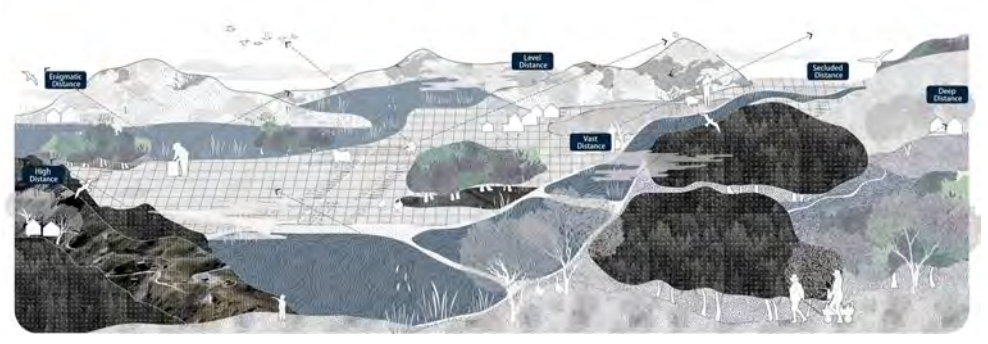

Fig. 8: Planning Illustration of the Six-Distance Scheme for the Site

Table 4: Meanings and Spatial Characteristics of the "Six Distances" in Shanshui Painting

Name	Classical Description	Spatial Characteristics
High Distance	Looking up from the foot of a mountain to its summit is called high distance.	Vertical height; sublimity.
Deep Distance	Looking from a near mountain toward a distant mountain is called level distance.	Layered depth (receding spatial strata).
Level Distance	Peering from the front of a mountain toward what lies behind it is called deep distance.	Lateral extension.
Vast Distance	Broad plains and vast rivers/lakes, where the far sky seems boundless, are called vast distance.	Expansive openness.
Enigmatic Distance	Mist and haze, where waters separate the view and what lies beyond appears indistinct, are called enigmatic distance.	Veiling; ambiguity.
Secluded Distance	When scenery reaches an extreme yet remains faint and ethereal, it is called secluded distance.	Emptiness; quietude; contemplative atmosphere.

4.3 Micro-Scale: Experiential Sequence of "Gazing, Traveling, Wandering, Dwelling"

We operationalize *shanshui* experiences through a dual "line and point" strategy. The line strategy structures routes following "Six Distances" and "walkable/viewable" principles. GIS viewshed analysis identifies high-value corridors, while route patterns extracted from paintings guide trail design and vantage point compositions. The point strategy deploys modular "habitable" units. Three painting-derived dwelling patterns are mapped onto buildable areas, with signature nodes like the "Recluse Dwelling" visualized through collage renderings articulating *shanshui* conceptions via local materials (Figs. 9-10).

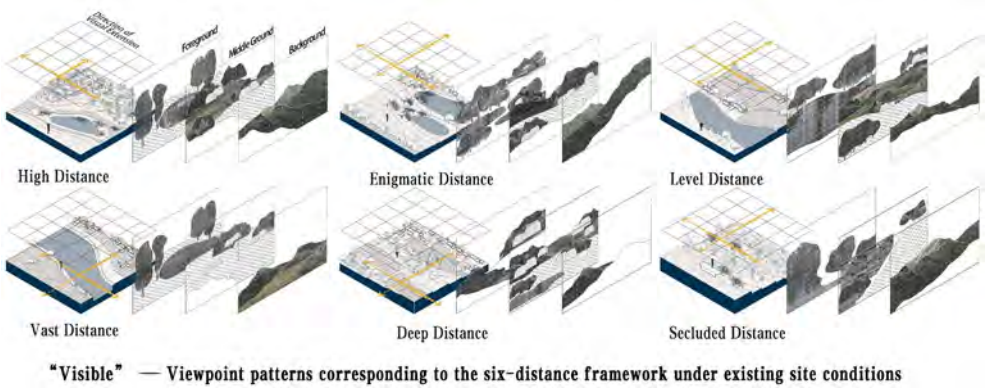

Fig. 9: Compositional patterns of Wufeng's Six-Distance scenes at specific on-site vantage points. The accompanying montage uses in-situ imagery from Wufeng to illustrate the actual scenes.

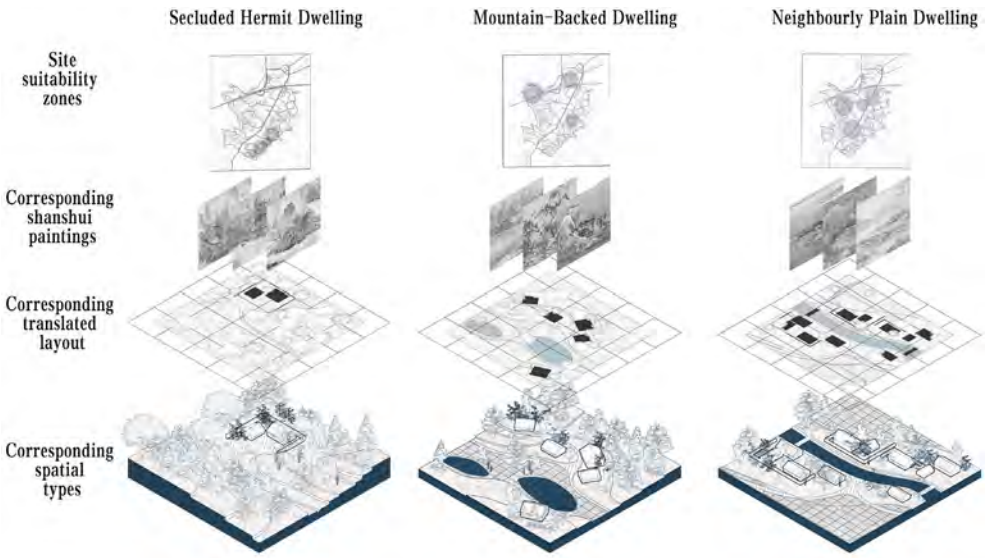

Fig. 10: Three "Habitable" Spatial Types and Their Corresponding Site Selection Areas

4.4 Quantitative Performance Evaluation

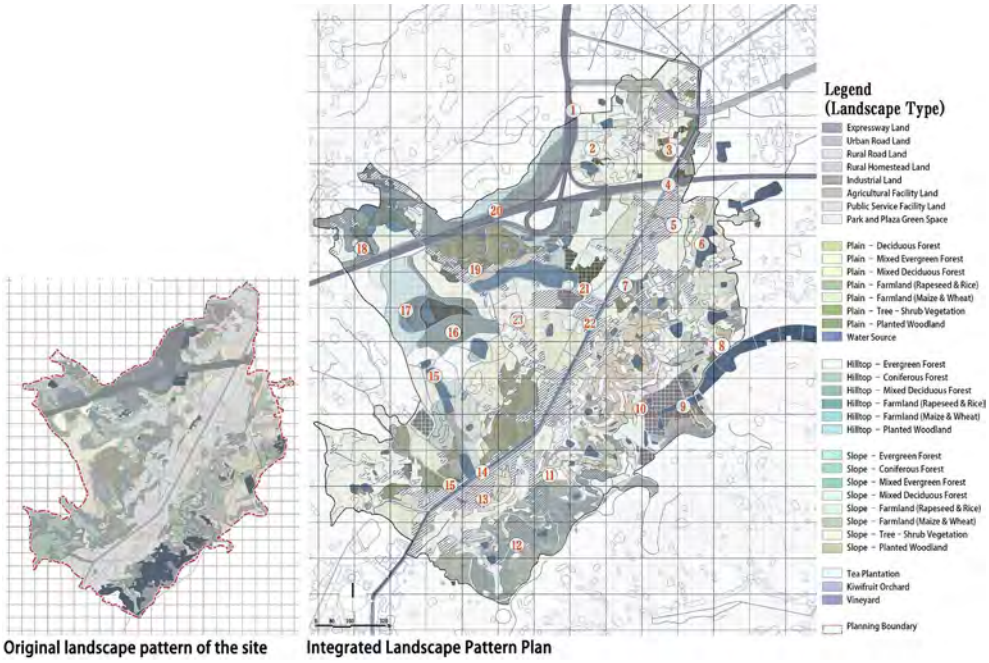

Fig. 11: Landscape Conditions Before and After Planning

Quantitative comparison against existing conditions shows the scheme improves ecological connectivity (PC index) by 18% via restored corridors. Viewshed analysis reveals a 31% increase in primary *shanshui* vistas within public spaces. Furthermore, optimized module placement reduces built land in flood-prone areas while improving 10-minute service accessibility from 63% to 82%, significantly enhancing both regional resilience and daily convenience (Fig. 11).

Discussion and Conclusion

This research formalizes *shanshui* spatial grammar into operational rules, establishing a reproducible pathway to integrate traditional culture into performance-driven planning. However, we critically acknowledge that GIS analytics evaluate the physical prerequisites and geometric armatures of *shanshui* spaces, rather than directly quantifying the ineffable *yijing* (artistic conception). Discretizing fluid cultural experiences involves reductionism; thus, fulfilling GIS metrics provides an optimized spatial "canvas" that facilitates and encourages, rather than guarantees, the intended cultural aesthetic. This framework functions as a decision-support tool to augment designer intuition. Future work will explore graph neural networks to capture deeper scene semantics for adaptive planning.

Acknowledgements

During the preparation of this work, the authors used ChatGPT and Gemini in order to improve the readability and polish the academic language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Network Morphology of Micro-Green Spaces in High-Density Urban Cores: A Comparative Case Study of New York, Paris, and London

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Abstract: Due to high population and building densities coupled with severe spatial fragmentation in high-density urban cores, constructing green space networks via structural connectivity – such as long-distance greenways and other linear green spaces combined with patchy green spaces – faces considerable challenges. This study focuses on micro-green spaces, a type gaining growing research and construction attention in recent years, to explore the potential functional connectivity network morphology based on this green space type. Taking Manhattan (New York), Petit Paris (Paris), and the Central Activities Zone (London) as case study areas, software including ArcGIS, Gephi, and Conefor was used to construct the network and analyse its structural characteristics and relevant network metrics. The results provide a scientific basis for micro-green spaces to serve as the main body for network construction in high-density urban cores in the future, and offer a reference for further research on the network morphology of micro-green spaces.

Keywords: Micro-green spaces, network structure, functional connectivity

1 Introduction

The micro-green space is a concept within the green space scale standard system, with specific area ranges varying across countries and regions. It is an urban green space that takes two-dimensional urban land as the basic spatial carrier, contains green natural elements of a certain scale, and undertakes certain public recreational service functions (ZHOU 2022). This study adopts the area definition specified in China's Standard (GB/T 51346-2019), defining the micro-green spaces involved as urban green spaces of less than 1 hectare, covering all green space types without functional restrictions.

Quantitative analysis of physical density in urban contexts mainly relies on population density and building density. LI et al., (2015) demonstrated through analytical work that a population density of 15,000 ppl/km² represents the threshold for classifying high-density cities, a finding that has gained widespread recognition and adoption among scholars in relevant fields. However, there is no universally accepted and accurate threshold value for building density. In response to this, this study selects population density as the criterion, focusing on spaces with a population density exceeding 15,000 ppl/km² or those with a slightly lower density but significant research value.

The urban core is a key component of the urban spatial structure, aggregating the city's core service functions and serving as a spatially contiguous area with intensive population activities and commercial intensity (KANG et al. 2021). Population and building densities in this

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area are higher than in other urban regions; in high-density cities, the importance and congestion of the core area are even more pronounced.

This research asks: how do unique urban morphologies influence the efficiency of these micro-networks? To what extent do they exhibit "small-world" characteristics that enhance urban resilience? And how do the varying mapping methodologies of global open data platforms affect our understanding of these patches?

Against this backdrop, taking micro-green spaces as the main body of the network and exploring potential functional connectivity network forms independent of structural connectivity can provide new scientific references for the construction and optimization of urban green space networks in such regions.

2 Methods and Data Processing

To ensure scientific rigor and replicability, this study merges research methodology with a detailed data processing workflow. The objective is to transform raw vector and spectral data into a quantifiable graph-theoretic model of functional connectivity.

2.1 Study Area

Based on a comprehensive analysis of rankings and population density data from the GaWC, the Global City Index (GCI), and the Husqvarna Urban Green Space Index (HUGSI), New York, Paris, and London – among top-tier global cities – were selected as case cities.

In line with the definition of urban cores, Manhattan (New York), Petit Paris (Paris), and the Central Activities Zone (CAZ, London) were designated as specific study areas for network construction and analysis.

2.2 Data Source

All data used in this study were sourced from open data platforms. Vector data for the New York study area were retrieved from NYC Open Data; those for the Paris study area from Paris Data; and those for the London study area from London Datastore. Land cover data and vegetation cover NDVI data were obtained from the European Space Agency, while elevation data were acquired from Open Topography.

2.3 Resistance Surface Construction and Multi-Factor Synthesis

The initial phase involves constructing a resistance surface to quantify the difficulty of movement across the urban core. Resistance is a measure of "ecological friction" – the cost incurred by an organism or person as they move from one point to another. Unlike rural models where resistance is primarily biological, urban resistance is predominantly physical and anthropogenic. Four factors were selected and weighted using the entropy weight method to minimize subjective bias:

1) Land Cover: Higher resistance is assigned to built-up areas and roads; lower resistance to vegetated surfaces.
2) NDVI (Normalized Difference Vegetation Index): Derived from ESA spectral data to reflect the actual density of biomass, regardless of administrative status.

3) Digital Elevation Model (DEM): Acquired from OpenTopography (Copernicus Global GLO-30), representing the top-reflective surface of the city, including buildings and infrastructure.
4) Slope: Calculated from the DEM to identify steep gradients that impede pedestrian movement and habitat suitability.

The choice of the entropy weight method is crucial because it allows the data's inherent information content to dictate the weights, preventing the over-emphasis of a single variable like land cover in areas where topography or vegetation density may play a larger role in connectivity.

2.4 Morphological Spatial Pattern Analysis (MSPA) and Software Rationale

MSPA, executed via the GuidoS toolbox, is selected as the primary tool for landscape segmentation. While traditional GIS methods merely identify patches, MSPA uses mathematical morphology – specifically erosion and dilation operations – to categorize patches based on their geometry and connectivity roles.

1) MSPA: In high-density cores, simple patch area metrics fail to capture the “edge effect” or the “bridging” potential of linear segments. MSPA distinguishes “Cores” (stable interiors) from “Islets” (isolated micro-patches) and “Bridges” (corridors connecting cores). This allows for a functional hierarchy of nodes.
2) ArcGIS: Used for spatial data visualization, resistance factor standardization, and initial vector processing. It is the industry standard for managing the complex administrative layers of global cities.
3) Conefor: Selected to calculate the Probability of Connectivity (dPC) index. dPC is a graph-theoretic metric that evaluates the contribution of each node to overall network integrity. It is particularly useful for identifying “choke points” or “hubs” where the loss of a single micro-patch would cause network collapse.
4) Gephi: Employed for topological transformation and large-scale network visualization. Gephi’s ForceAtlas2 and modularity algorithms are uniquely capable of identifying community clusters within the city-wide network.

2.5 Addressing Mapping Bias and Data Consistency

A significant methodological challenge in this comparative study is the variation in how NYC, Paris, and London map their green spaces. To ensure methodological consistency, it is necessary to address the inherent mapping biases and disparate data protocols utilized by each city’s open data platform. In New York, the NYC Open Data platform relies on polygons digitized by permit offices for event management, which often leads to the over-segmentation of large, continuous parks into multiple small polygons. Paris Data utilizes a system of 13 administrative categories (e. g., 'Jardins', 'Squares'), a protocol that may exclude informal greening features such as railway talus. Meanwhile, London’s GiGL dataset achieves high structural accuracy by snapping to Ordnance Survey MasterMap features but frequently excludes private gardens from its public records.

To mitigate these discrepancies, this study employs a “spectral equalization” strategy. We utilize Morphological Spatial Pattern Analysis (MSPA) on a unified 10m-resolution NDVI binary mask derived from ESA WorldCover data. This approach ensures that patches are defined by their actual physical biomass rather than administrative permits, allowing for a truly objective comparative assessment of micro-green morphology.

2.6 Threshold Selection and Small-World Metrics

The construction of network "edges" (connections) requires a distance threshold. A 1,500-meter threshold was adopted, representing a strategic balance between the "15-minute city" pedestrian walking radius and the moderate dispersal distance of urban-adapted avian species. This dual justification ensures the network is relevant for both social and ecological functions.

Since the introduction of descriptive metrics (DUNCAN et al. 1998), Humphries and Gurney proposed quantitative assessment criteria for small-world networks (HUMPHRIES & GURNEY 2008):

$$\sigma = \left(\frac{C/C_{random}}{L/L_{random}}\right) > 1$$

Among these, the calculation methods for C_{random} and L_{random} are derived from classical random graph theory (ERDŐS & RÉNYI 1959). C_{random} represents the expected probability that any two neighboring nodes are also connected to each other in a random network. In an ecological context, this can be extended to mean the probability that any two patches connected to the same patch are also directly linked, assuming corridors are randomly connected in an ecological network.L_{random} denotes the average number of "steps" required between any two nodes in a random network. Ecologically, this translates to the minimum number of steps needed to reach most other patches in a large ecological network where biological dispersal occurs randomly, starting from a single patch.

3 Results

Based on the above definition of micro-green spaces, the distribution maps of filtered micro-green spaces in each study area are presented below (Fig. 1).

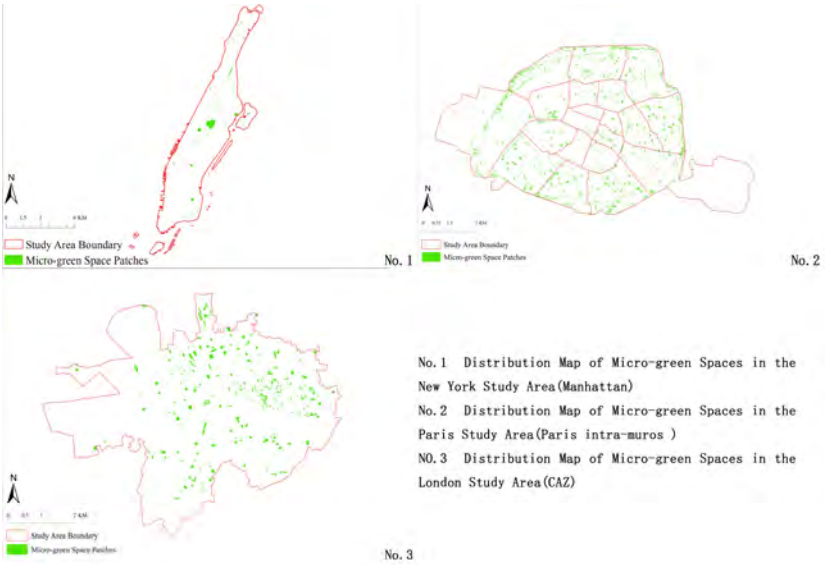

Fig. 1: Distribution Map of Micro-Green Spaces in Study Area

Following resistance surface construction, the distribution maps of resistance values are presented below (Fig. 2).

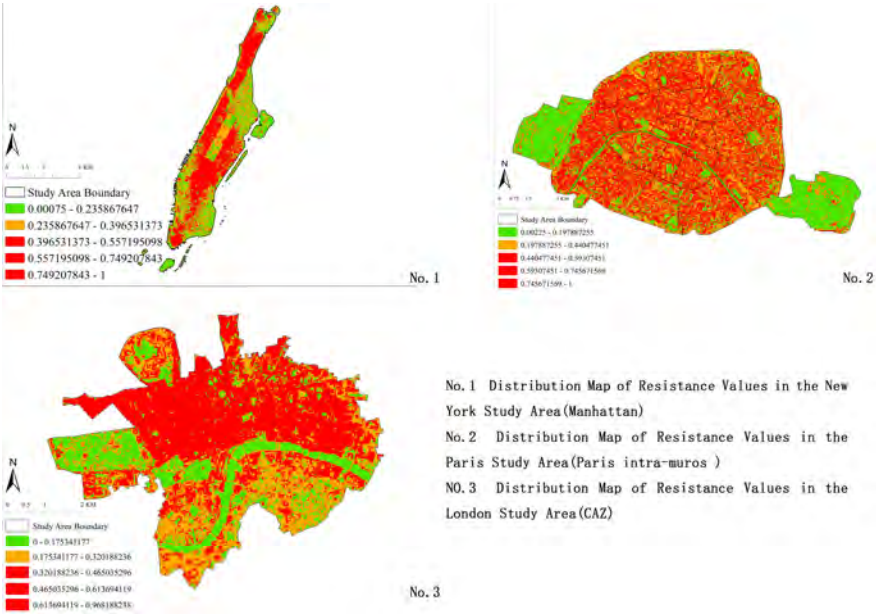

Fig. 2: Distribution Map of Resistance Values in Study Area

Probability of connectivity (dPC) values were calculated for all nodes, and edges were constructed using a 1,500-meter distance threshold. Nodes were filtered based on dPC values falling within the top two classes of the natural breaks classification, designated as core hubs and major hubs respectively. Correspondingly, edges connecting two core hubs or linking core hubs to major hubs were identified as backbone corridors and secondary corridors. These selected nodes and corridors were extracted to collectively form the backbone potential functional connectivity network of micro-green spaces. The network distribution and topologically processed results are presented below (Figs. 3-8).

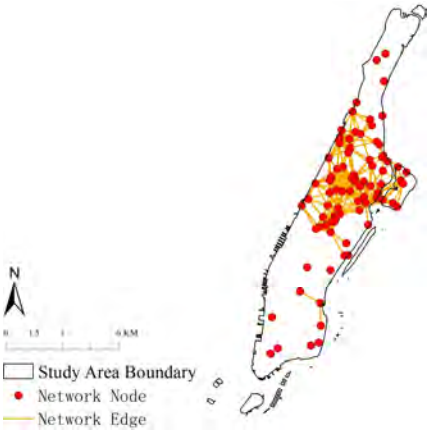

Fig. 3:
Potential Functional Connectivity Network Map of Micro-Green Spaces in the New York Study Area

Fig. 4:
Topology Map of the Backbone Potential Functional Connectivity Network of Micro-Green Spaces in the New York Study Area

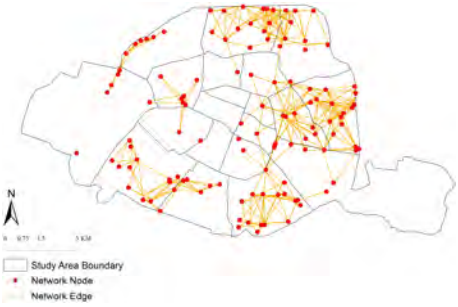

Fig. 5:
Potential Functional Connectivity Network Map of Micro-Green Spaces in the Paris Study Area

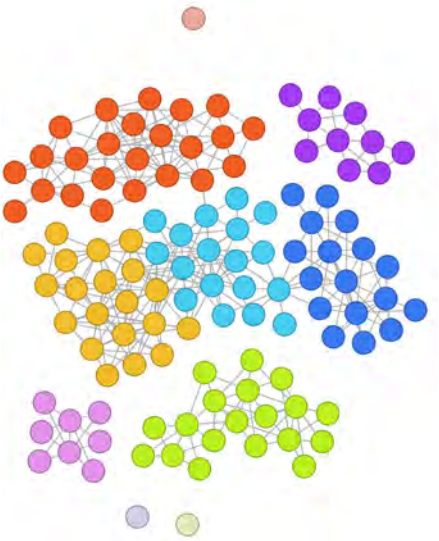

Fig. 6:
Topology Map of the Backbone Potential Functional Connectivity Network of Micro-Green Spaces in the Paris Study Area

Fig. 7:
Potential Functional Connectivity Network Map of Micro-Green Spaces in the London Study Area

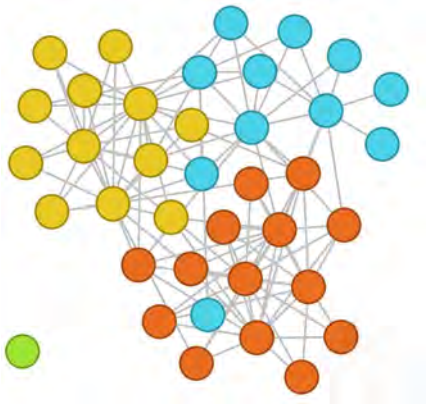

Fig. 8:
Topology Map of the Backbone Potential Functional Connectivity Network of Micro-Green Spaces in the London Study Area

For network-related metrics, six indicators – average degree, network diameter, average path length, average clustering coefficient, modularity, and graph density – were selected to quantitatively describe the network structure. The specific calculated values are presented in the table below.

Table 1: Specific calculated values

Study Area	Number of Nodes	Number of Edges	Average Degree	Network Diameter	Average Path Length	Average Clustering Coefficient	Modularity	Graph Density
New York	84	318	7.571	7	2.906	0.540	0.489	0.091
Paris	119	351	5.899	11	4.143	0.628	0.736	0.050
London	38	115	6.053	5	2.348	0.641	0.420	0.164

Based on the above analysis, this study used the calculated σ values as the primary determination criterion, combined with the descriptive indicators of average clustering coefficient and average path length, to conduct structural identification of the backbone networks of micro-green spaces in the three study areas. The calculated σ values for New York, Paris, and London are approximately 4.514, 8.232, and 3.462, respectively – all greater than 1.

Thus, the networks in all three study areas can be classified as small-world network structures.

Furthermore, based on the previously calculated network metrics, the average clustering coefficients of 0.540, 0.628, and 0.641 are all at relatively high levels, while the average path lengths of 2.906, 4.143, and 2.348 are all at relatively low levels. From the perspective of descriptive determination criteria, these findings further corroborate the classification of the networks as small-world structures based on σ values.

4 Conclusion and Outlook

4.1 Resistance Surface Characteristics

Based on the results of resistance surface construction, the distribution of resistance values classified via the natural breaks method exhibits distinct high-value clustering characteristics. Resistance value "valleys" (green areas) – the most suitable zones for constructing structural connectivity corridors – are small in size and scattered, while resistance value "peaks" (orange and red areas) are predominant in area and relatively continuous in distribution. Overall, these peaks form absolute barriers that completely impede corridor construction.

Drawing on these resistance surface findings, this study argues that constructing urban green space networks based on structural connectivity – relying on the traditional "patch-corridor-matrix" theory – is highly challenging within the unique context of high-density urban cores. Future planning must transition from "topology optimization" to "quality optimization." Once the backbone network is identified, planners should target nodes with low biomass (low NDVI) for enrichment planting to maximize their resistance-reducing capacity. The "stepping-stone" utility of a micro-patch is only realized if its internal quality supports the target "flow". Alternative network construction approaches should therefore be explored.

4.2 Network Structure

Furthermore, beyond shared attributes such as small-world characteristics and community modularity, the network structures across the disparate study areas exhibit idiosyncratic morphological traits. These unique topological signatures are categorized into distinct patterns as follows:

(1) The backbone network of micro-green spaces in the New York study area comprises 84 nodes and 318 edges. With an average degree of 7.571 – the highest among the three case cities – and a relatively high graph density of 0.091, it reflects extremely tight connections between nodes. This dense spatial connectivity pattern aligns with New York's intensive grid system. Additionally, comparative analysis of node importance reveals 30 core hubs in the New York study area, accounting for 7.59% of the total – the highest proportion among the three cities – indicating distinct core hub-oriented network characteristics. In summary, the relative characteristic of the potential functional connectivity network of micro-green spaces in the New York study area is a dense-connected, core-oriented network.

(2) The potential functional connectivity network of micro-green spaces in the Paris study area has a modularity Q-value of 0.736, the highest among the three case cities. Visual analysis of the corresponding backbone network diagram shows relatively clear boundaries between community structures, indicating the most prominent network community structure.

With 119 nodes and 351 edges, the network forms multiple relatively independent functional clusters, which align with the 20 administrative and functional districts of central Paris. Each cluster centers on a small number of core hubs and is distributed with functional connectivity corridors, forming a pattern of "high-density intra-cluster connections" and "backbone corridor inter-cluster connections" that prevents network fragmentation. Combined with Paris's concentric radial spatial planning model, the study area has the longest average path length (4.143) among the three cities, with network communities connected by limited, long-distance functional corridors, presenting a radial structural pattern. In summary, the relative characteristic of the potential functional connectivity network of micro-green spaces in the Paris study area is a high-modularity, radial network.

(3) London has the highest average clustering coefficient (0.641) among the three case cities. Its backbone network contains only 38 nodes – the fewest among the three – but achieves the highest graph density of 0.164. These indicators collectively reflect the highly clustered and compact characteristics of micro-green spaces in the London study area, corresponding to the compact land use features of the Central Activities Zone (CAZ). Furthermore, with 115 edges in its backbone network, London has the lowest average path length of 2.348. The potential functional connectivity network of micro-green spaces in the London study area constructs a relatively dense network structure with a small number of nodes, demonstrating an efficient connectivity pattern overall. This characteristic meets the requirement for efficient service provision from ecological spaces. In summary, the relative characteristic of the potential functional connectivity network of micro-green spaces in the London study area is a highly clustered, efficient connectivity network.

4.3 Outlook

While this report provides a comprehensive static analysis, the "outlook" for micro-green space research involves the integration of two critical dynamic variables: population density and distance sensitivity.

1) Population Density as a Dynamic Pressure

Current research, including this study, identifies high-density cores using a static threshold (>15,000 ppl/km^2). However, population density should be viewed as a dynamic "demand" variable. A micro-green space in a high-density residential zone (URZ) faces different pressures – and provides different social services – than one in a commercial office district (XU et al. 2021). Future studies should integrate mobile phone big data or POI (Point of Interest) data to weight the "social importance" of nodes, creating a hybrid socio-ecological dPC index.

2) Threshold Sensitivity and Percolation Theory

The 1,500-meter threshold used here is a compromise. Sensitivity analysis – testing the network at 400m (pocket park standard), 800m (pedestrian limit), and 2,000m (avian flight) – would reveal the "percolation threshold" of the city. Identifying the exact distance at which a fragmented network suddenly "connects" into a global whole is vital for understanding the tipping points of urban ecological health (ZHOU 2023).

3) Global Sample Expansion

The insights gained from New York, Paris, and London provide a benchmark for other global metropolises. Expanding the sample size to include Asian "megacities" (e. g., Tokyo, Hong Kong, Shanghai) or developing-world cores (e. g., Mumbai, São Paulo) would allow for a

more robust extraction of network characteristics across different economic and geographical contexts.

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Construction of a Multi-Dimensional Evaluation Model for Rural Ecological Landscapes Based on a Digital Platform

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Abstract: Rural ecological landscapes are shaped by coupled natural processes and human activities, yet practical evaluation and governance often remain constrained by fragmented datasets, indicator inconsistency, and limited decision-support efficiency. To address these gaps, this study constructs a multi-dimensional evaluation model for rural ecological landscapes and embeds it into a modular digital platform to enable integrated data management, standardized computation, and visual decision support. The model is organized into four dimensions – ecological baseline conditions, landscape spatial structure, ecosystem service functions, and ecological risk response – forming a state-organization-output-pressure logic chain. A platform-enabled workflow is established to orchestrate multi-source data harmonization, algorithmic execution, and interactive visualization. A pilot study in Huangshandian Village, Beijing, is utilized to validate both the ecological applicability of the model and the operational effectiveness of the platform. Results demonstrate that the multi-dimensional model accurately captures complex spatial differentiations, successfully identifying high-quality conservation cores in peripheral natural areas and elevated composite risks in the central development corridor. Simultaneously, the platform's automated geoprocessing engine proved effective in resolving data interoperability issues and executing these complex diagnostics without requiring fragmented GIS operations. Furthermore, the interactive frontend visualization empowers non-expert stakeholders to dynamically generate and query comprehensive ecological grading maps. Overall, this study contributes a scientifically robust ecological evaluation framework and operationalizes it through an accessible digital platform, transforming traditional fragmented analyses into an integrated planning support system for data-driven rural governance.

Keywords: Rural ecological landscape, digital platform, multi-dimensional evaluation model, multi-source data integration, spatial decision support

1 Introduction

The *Rural Revitalization Plan* (2024-2027), officially released by the Central Committee of the Communist Party of China and the State Council in January 2025, emphasizes technological innovation and accelerated digital development in rural areas. Rural areas, as complex socio-ecological systems, are essential for biodiversity conservation, regional climate regulation, and environmental quality enhancement, while also supporting agricultural production and rural livelihoods (WANG et al. 2024). However, many rural regions are increasingly challenged by extensive land use, declining ecological functions, and weak resilience. Traditional practices often rely on expert judgment and lack systematic, dynamic, and data-driven capabilities required for ecological management, underscoring the need for digital approaches in planning and governance (WANG et al. 2021).

To address these limitations, Geographic information systems, artificial intelligence technologies, and integrated digital platforms are increasingly being applied to the field of rural ecological research (CHEN & WANG 2022, ZHOU et al. 2024), establishing new pathways for

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data acquisition, environmental monitoring, and ecological risk analysis. For instance, Yuan et al. (2023) used digital twin technology to build a comprehensive digital model of rural landscapes, enabling spatial integration and dynamic visualization of ecological and morphological data. Piras et al. (2025) introduced a spatiotemporal assessment framework that combines historical remote sensing and ground monitoring data to reveal landscape vulnerability and ecological pattern evolution over time. Zhang et al. (2024) developed a digital twin-based simulation model for traditional village landscape restoration, supporting virtual analysis of soil erosion and vegetation recovery. Despite these advancements, most existing applications remain fragmented, focusing on single-purpose scenarios or static analysis. There is a lack of end-to-end platforms that allow non-technical stakeholders to seamlessly integrate heterogeneous data, execute complex ecological evaluations, and visualize risks within a unified workflow.

Consequently, there is a pressing need for an integrated digital system adaptable to the practical realities of rural governance. This study proposes a multi-dimensional evaluation model embedded in a modular digital platform, specifically targeting rural planners and village administrators during diagnostic and monitoring phases of spatial planning. Instead of relying on fragmented datasets, the proposed framework systematically integrates remote sensing imagery, land use surveys, and ecological zoning data to assess four key dimensions: ecological baseline, spatial structure, ecosystem services, and ecological risks. This platform-enabled assessment approach aims to bridge the gap between theoretical metrics and practical application, providing a replicable, data-driven pathway to support transparent decision-making and precise ecological restoration in rural areas.

2 Methods

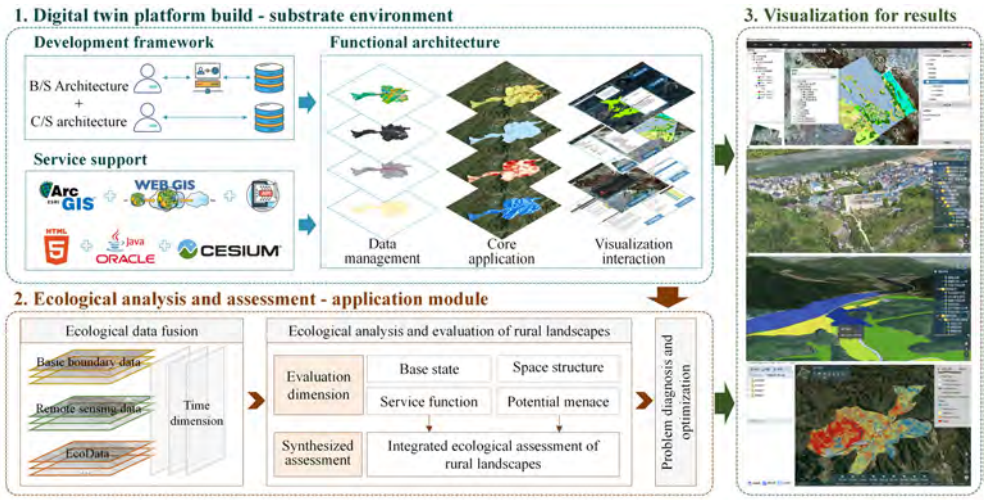

Fig. 1: The framework for rural landscape ecological evaluation based on a digital twin platform

To support a comprehensive and data-driven evaluation of rural ecological landscapes, we develop the methodological framework (**Fig. 1**) that integrates digital platform development, ecological indicator system construction and field application.

2.1 Platform Construction for Digital Twins of Rural Ecological Landscapes

To facilitate end-to-end rural ecological landscape evaluation and balance intensive spatial analytics with broad accessibility, the system adopts a modular, hybrid computational architecture. The backend leverages ArcGIS Engine and ArcGIS Server to efficiently handle multi-source data integration, complex indicator calculation, and heavy geoprocessing tasks. Conversely, a lightweight HTML5 and WebGL frontend enables seamless cross-device access. This allows rural administrators to interact with comprehensive ecological grading and 3D visualizations directly via web browsers, eliminating the need for specialized desktop software.

Within this hybrid framework, the core functionality of the digital twin under investigation involves generating twin data and constructing twin models within a specific digital environment, supporting spatiotemporal diagnostics and visual decision support. To ensure robustness and scalability, the platform employs a six-layer hierarchy (Fig. 2). The foundational levels, comprising the Infrastructure, Data Resource, and Service Support layers, handle data acquisition, standardization, and cybersecurity to create a reliable digital substrate. Furthermore, the upper Presentation and User Access tiers manage role-based permissions and interactive visualization. Ultimately, this layered configuration effectively integrates powerful backend spatial engines with intuitive frontend accessibility for practical rural governance.

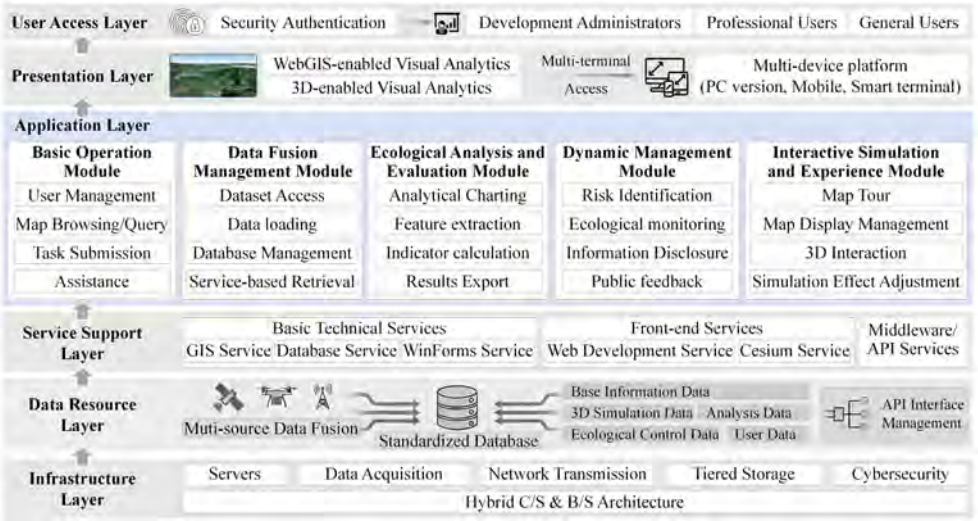

Fig. 2: Overall platform architecture

Central to this architecture is the Application Layer, which orchestrates domain-specific workflows through five interconnected modules. The Basic Operation Module handles user authentication, map browsing, and task submission, while the Data Fusion and Management Module oversees dataset access and service-based retrieval. The core Ecological Analysis and Evaluation Module drives spatial computation to produce indicator layers and integrated grading maps. For ongoing monitoring, the Dynamic Management Module tracks land-use changes and risk factors, enabling issue annotation and risk identification. Finally, the Interactive Simulation and Experience Module links WebGIS with 3D rendering, offering hierarchical browsing and scenario-based interpretation to improve communication efficiency.

2.2 Development of a Rural Ecological Landscape Evaluation Model

A computational evaluation model was developed to transform multi-source spatial data into quantifiable ecological diagnostics, supporting the assessment of rural ecological landscapes. Its automated, standardized workflow ensures accessibility for non-experts, including rural planners and village administrators.

2.2.1 Ecological Evaluation Framework

To capture the interplay between natural processes and anthropogenic interventions, the evaluation model follows a State-Organization-Output-Pressure logic chain. This framework links physical conditions to management actions, enabling the identification of causal pathways for ecological degradation. The indicator system (Tab. 1) comprises four dimensions, selected based on ecological significance, data availability, and computational feasibility.

Table 1: Rural ecological landscape evaluation system

Dimension	Indicator	Indicator description
Ecological baseline	Terrain relief	Calculated based on slope and elevation variation derived from DEM data. It reflects the complexity of the terrain and its constraint on the spatial distribution.
	Vegetation sensitivity	Derived from NDVI and FVC indices in combination with land cover metrics. This indicator reflects the responsiveness of the vegetation system.
	Hydrological sensitivity	Calculated based on stream density and overlap with catchment areas. It indicates the region's sensitivity to water resource dynamics.
Spatial structure	Connectivity index	Assessed based on minimum distances between ecological patches, this index measures the degree of ecological connectivity and ecological flows.
	Fragmentation index	Calculated based on the number of patches, average patch area, and edge complexity. It quantifies the degree of ecological fragmentation.
	Spread Index	It reflects the spatial aggregation and expansion trends of different patch types, revealing the overall accessibility and continuity of the landscape structure.
Ecosystem services	Water conservation index	Estimated using the water yield module in the InVEST model, this index reflects the capacity of a region to regulate precipitation and runoff.
	Carbon storage density	Derived from field surveys, biomass equations, or inversion using NDVI and LiDAR models. It reflects the ecosystem's ability to fix atmospheric carbon.
	Biodiversity maintenance index	Calculated using landscape diversity indices or species abundance models, this indicator reflects the ability of an ecosystem to maintain biodiversity.
Ecological risk response	Flood risk index	Derived using a weighted overlay of terrain depressions, impervious surface ratio, and rainfall intensity. It reflects the potential risk of flooding.
	Population density	Based on statistical population data per unit area. It represents the potential anthropogenic pressure on ecosystems.
	Land development intensity	Calculated as the proportion of construction land in current land use maps. It reflects the degree of land development and its disturbance pressure.

The Ecological Baseline focuses on the physical environment (e. g., topography, vegetation sensitivity) to provide the static background for the digital representation. The Spatial Structure reflects the stability of landscape patterns using landscape ecology metrics (e. g., connectivity, fragmentation). The Ecosystem Services dimension assesses the functional capacity of the landscape to quantify benefits provided to rural communities. Finally, Ecological Risk Response identifies vulnerabilities to natural hazards and development intensity, highlighting areas requiring targeted governance.

2.2.2 Algorithmic Integration and Service Encapsulation

To bridge the gap between theoretical metrics and practical application, the evaluation framework was operationalized through a hybrid integration strategy that distinguishes between lightweight internal computations and the coupling of specialized external models. For fundamental indicators such as terrain relief and vegetation sensitivity, the calculation logic is directly encapsulated into server-side Python scripts using standard GIS libraries. These internal services handle data preprocessing and spatial overlay tasks efficiently, providing immediate feedback via the frontend interface.

In contrast, for complex ecological assessments – specifically the InVEST model for ecosystem services and Fragstats for landscape pattern analysis – the platform adopts a loose-coupling mechanism. Instead of embedding these computationally intensive engines directly into the web architecture, the system functions as a data mediation layer. It standardizes multi-source input datasets into formats compatible with these professional models and facilitates their invocation. The resulting outputs are then ingested back into the platform for normalization and weighted overlay. Through this coordinated workflow, the platform effectively orchestrates the evaluation process, shielding users from the tedious tasks of data format conversion and parameter configuration, thereby transforming a fragmented multi-software operation into a streamlined, integrated digital service.

3 Results

Huangshandian Village in Beijing was selected as a pilot case to validate the platform's operational feasibility and analytical capabilities. These results demonstrate the system's effectiveness in data integration, multi-dimensional evaluation, and visual decision support.

3.1 Platform-Driven Data Integration and Standardization

Covering approximately 12.7 km² in Changping District, the study area represents a typical rural landscape in the transitional zone between plains and low mountains, characterized by a complex mosaic of agricultural land, forested areas, and built-up settlements. Deploying the system in this setting provides a real-world governance context to examine the interoperability of the model integration framework and the platform's capacity to support multidimensional ecological assessments.

To establish the digital foundation for this evaluation, the platform's data management module integrated a multi-source acquisition scheme comprising GNSS-based field measurements, high-resolution remote sensing products, and environmental monitoring datasets. The system facilitated the standardization of all heterogeneous inputs to the CGCS2000 coordi-

nate system through consistent spatial registration, temporal alignment, and numerical normalization. In areas with sparse ground monitoring, ordinary Kriging interpolation was applied within the workflow to generate continuous surface layers. These interpolated products were subsequently combined with high-resolution imagery and digital surface models to accurately represent terrain, vegetation structure, and the built environment. Ultimately, the system consolidated these inputs into an integrated ecological factor database encompassing eight data dimensions, including hydrology, land use, and anthropogenic factors, which collectively provide the standardized data foundation for the subsequent model-driven evaluation (Tab. 2).

Table 2: Ecological Factor Database of the Rural Landscape in Huangshandian Village

Data Dimension	Main Data Types	Format
Remote sensing and environmental monitoring	High-resolution imagery; surface dryness, moisture, and temperature; digital terrain model, etc.	GeoTIFF / Shapefile
Terrain and topography	DEM; slope; aspect; slope length	GeoTIFF
Hydrology and soil	River network; runoff basins; soil type; erosion modulus	Shapefile / GeoTIFF
Vegetation and biodiversity	Vegetation types; NDVI; NPP	Shapefile / GeoTIFF
Land use and built features	Land use classification; roads; buildings; zoning boundaries	Shapefile / GeoTIFF
Anthropogenic factors	Population density; infrastructure layout	GeoTIFF / Shapefile
Administrative boundaries	Village boundaries; planning overlays	Shapefile
Meteorological records	Precipitation; air temperature	GeoTIFF

3.2 Algorithmic Execution of the Multidimensional Assessment

Leveraging the integrated spatial database, the platform executed the evaluation framework to demonstrate its analytical capabilities. The platform-based assessment results for Huangshandian Village across the four dimensions (**Fig. 3**) illustrate the system's effectiveness in translating raw heterogeneous data into spatially explicit diagnostics.

Driven by internal geoprocessing services, the platform's evaluation component successfully processed the natural baseline indicators (**Fig. 3**a-d). The calculation engine accurately delineated spatial gradients, mapping higher topographic variability in the southwestern sectors and a distinct west-to-east vegetation sensitivity gradient. By synthesizing these factors, the system generated a composite baseline map that correctly contrasted the high-scoring foothill areas with the lower-scoring intensive-use zones. Similarly, the platform's spatial structure algorithms (**Fig. 3**e-h) effectively quantified landscape connectivity and fragmentation. The resulting outputs clearly visualized the barrier effect of the central settlement-road belt on patch continuity, demonstrating the engine's precision in capturing complex spatial layouts.

For the ecosystem services evaluation (**Fig. 3**i-l), the platform employed its hybrid integration strategy, acting as a data mediation layer to couple with specialized external models. The system successfully aggregated outputs regarding water source conservation, carbon storage, and biodiversity maintenance, highlighting a prominent service hotspot in the southwestern

forested areas. In evaluating ecological risk response (**Fig. 3**m-p), the platform orchestrated a weighted spatial overlay of flood risk, population density, and land development intensity. The workflow accurately pinpointed vulnerability concentrations within the central corridor, clearly distinguishing them from the low-risk peripheral forests.

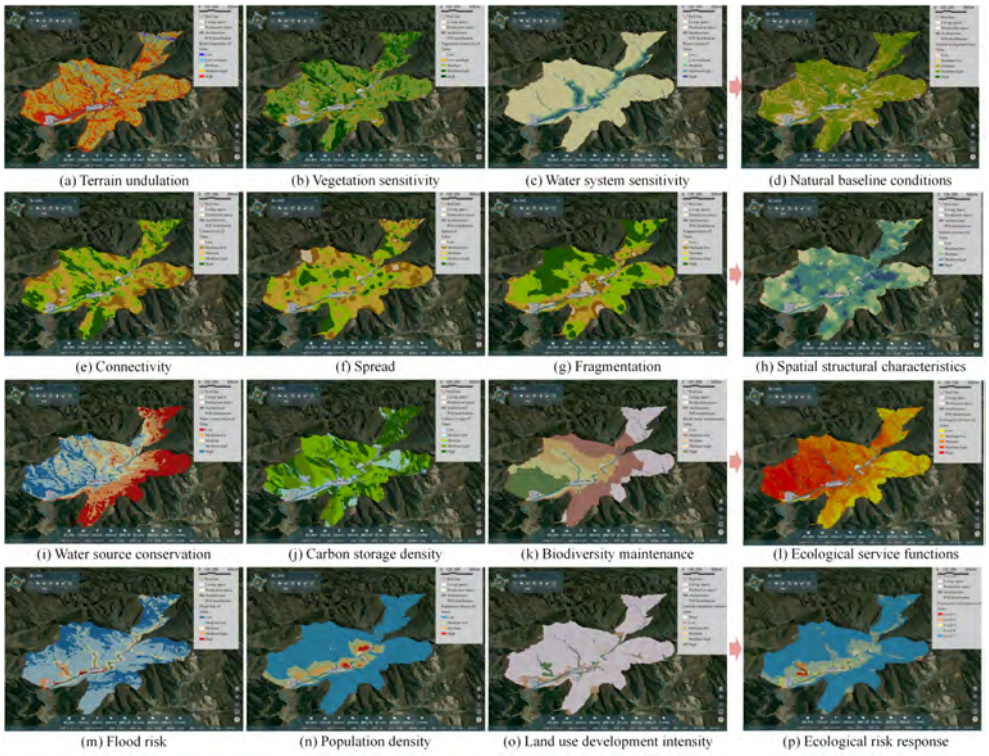

Fig. 3: Results of the unidimensional analysis of the ecological landscape of Huangshandian village

Across all four integrated outputs, the platform-generated maps revealed a consistent spatial contrast between the peripheral natural areas and the central development corridor. By successfully mapping these coupled relationships – where peripheral areas exhibit robust baseline quality and the central corridor shows elevated composite risks – the system proved its capability to execute multidimensional ecological assessments. The results confirm that the platform can effectively analyze, synthesize, and visualize complex ecological configurations.

3.3 Interactive Visualization and Spatial Decision Support

To evaluate the platform's capacity for comprehensive spatial decision support, the integrated evaluation module executed an AHP-based weighted overlay, synthesizing the four-dimensional outputs into a final ecological quality grading map (Fig. 4). Rather than functioning merely as a static map generator, the system accommodates localized planning priorities by

allowing users to adjust indicator weights through its frontend interface. The resulting visualization successfully delineates a clear spatial differentiation across the village, proving the platform's effectiveness in translating complex, multidimensional data into an actionable zoning layout.

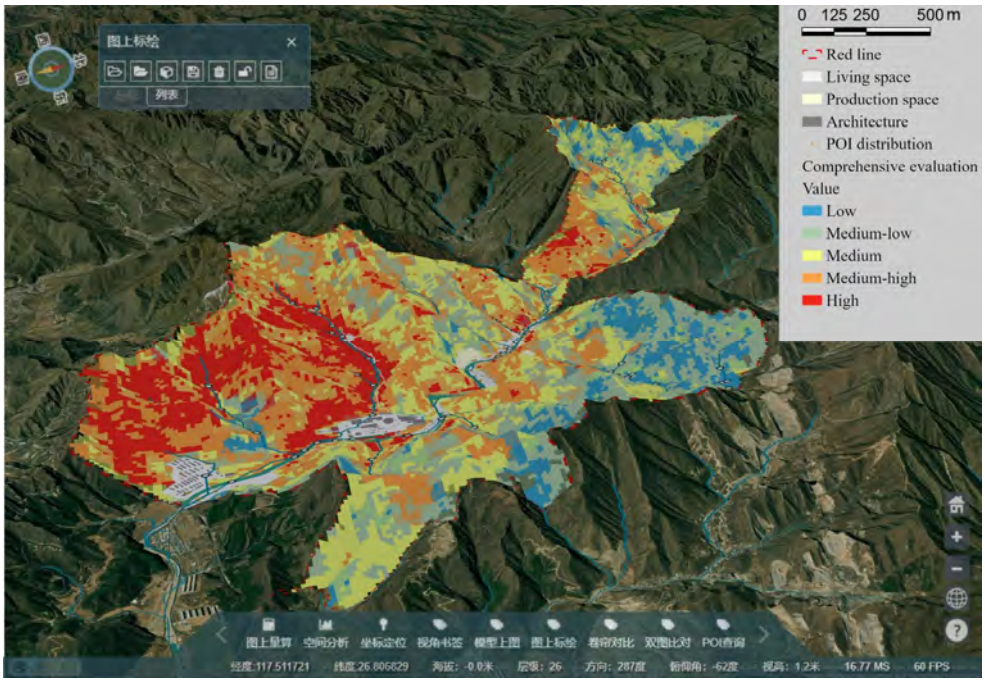

Fig. 4: Integrated ecological quality analysis results of Huangshandian village

The visualization engine accurately highlighted high ecological quality zones predominantly concentrated in the western mountainous area, where the system computed continuous ecological land covers and strong service-supporting conditions. In contrast, the spatial analysis identified low to medium-low grades clustered in the eastern sector and along the central development corridor. These areas were correctly mapped to reflect the cumulative disturbance pressure and reduced structural integrity associated with built-up land and intensive production activities. Crucially, the platform translates these integrated outputs into an accessible format for stakeholders without specialized GIS training. By rendering layered visualizations and enabling interactive querying of the grading outputs, the system allows users to intuitively locate priority zones for differentiated management, such as conservation cores in the west and restoration interventions in the central corridor. This interactive capability demonstrates that the resulting technology functions effectively as a practical planning support system, empowering users to trace the specific data contributions from individual ecological dimensions and make transparent, evidence-based governance decisions.

4 Discussion

The application of the proposed digital platform in Huangshandian Village highlights a necessary paradigm shift in rural ecological landscape evaluation, transitioning from static, fragmented GIS analyses to dynamic, integrated planning support systems. Traditional ecological assessments heavily rely on manual data processing and iterative software switching – such as transferring raster datasets between ArcGIS, InVEST, and Fragstats – which severely limits the efficiency and reproducibility of the evaluation process (VONK et al. 2005). In contrast, the results demonstrate the high effectiveness and modularity of the platform's hybrid integration strategy. By functioning as a data mediation layer, the system automates spatial registration and algorithmic orchestration. This modular architecture not only streamlines the immediate computational workflow but also ensures long-term system extensibility; external models or internal evaluation indicators can be updated or replaced independently without requiring a complete overhaul of the core web framework.

Furthermore, the platform significantly enhances the accessibility of complex ecological theories for practical governance. Landscape ecology concepts, such as the evaluation framework and connectivity metrics, traditionally present a steep learning curve for non-technical rural administrators and local planners. The proposed system addresses this bottleneck by encapsulating complex Python scripts and geoprocessing services within the backend architecture, exposing only an interactive, intuitive frontend interface. As demonstrated by the real-time ecological quality grading outputs, stakeholders can adjust multidimensional evaluation weights based on localized planning priorities and immediately visualize the spatial consequences. This interactive capacity democratizes access to evidence-based spatial diagnostics (TAN & CHENG 2024), allowing decision-makers to focus on formulating ecological redlines and restoration strategies rather than struggling with technical execution.

Despite these advancements, several limitations must be acknowledged. First, diagnostic performance is constrained by data quality, spatial resolution, and temporal availability. In data-sparse rural areas, reliance on static remote sensing reduces assessment reliability, necessitating the future integration of continuous monitoring sources to improve spatial fidelity. Second, while the platform establishes a foundational digital twin substrate for mapping and analysis, the closed-loop linkage for real-time virtual updating remains limited. Advancing toward a mature digital-twin paradigm requires integrating IoT sensor networks and automated feedback mechanisms. Finally, the current algorithmic engine focuses on diagnostic evaluation rather than predictive capacity. Integrating machine learning for dynamic scenario simulation and risk forecasting represents a critical extension. These developments will significantly enhance the platform's ability to support adaptive management and fine-grained ecological governance.

5 Conclusion and Outlook

This study presents a modular, data-driven digital platform with digital twin features for rural ecological landscape evaluation. By integrating multi-source heterogeneous datasets with a multi-dimensional indicator framework, the platform supports standardized computation and intuitive visualization of ecological conditions, ecosystem service performance, and risk-related pressures. The Huangshandian Village case study demonstrates the feasibility and in-

teroperability of the platform workflow, and indicates its practical value for identifying conservation-priority areas and risk-prone zones to inform planning and management.

Future research will focus on evolving the platform from a diagnostic evaluation tool into a dynamic, real-time digital twin. This transition will require overcoming current data dependencies by integrating high-frequency monitoring streams, such as IoT sensor networks, to improve data timeliness and model transferability across diverse rural contexts. Furthermore, advancing the platform's external model coupling to include machine learning and predictive scenario-based analysis will significantly expand its functionality. These technological enhancements will provide continuous, forward-looking decision support, facilitating adaptive management toward resilient and sustainable rural landscapes.

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Three-Dimensional Characterization of Urban Green Space for Cooling Effect Based on LCZ Classification

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Abstract: The three-dimensional characteristics of urban green spaces and buildings play a crucial role in regulating the thermal environment. This study focuses on the main urban area of Nanjing, using the Local Climate Zone (LCZ) classification system to explore the three-dimensional characteristics of green space based on urban spatial structure. After consistency validation using the Weather Research and Forecasting model coupled with the Building Effect Parameterization urban canopy scheme (WRF-BEP), near-surface 2-meter air temperatures were obtained. SHAP was then used to identify key three-dimensional features and their response characteristics that are most closely associated with temperature variation in different LCZ types. The results show that the contribution of three-dimensional feature indicators to temperature prediction varies significantly across different LCZ types and exhibits non-linear relationships, especially for plant height standard deviation (THstd), three-dimensional structure-to-green space ratio (TGR), and building-to-vegetation volume ratio (BTVR). The study introduces the LCZ classification, breaking through traditional two-dimensional perspectives, and reveals the relationship patterns between the three-dimensional characteristics of urban green spaces and the thermal environment in high-temperature areas. The findings provide structural references for optimizing urban green space systems and designing based on cooling demands.

Keywords: LCZ, three-dimensional indicators, cooling effect, urban green space, urban thermal environment

1 Introduction

Urbanization has rapidly increased impervious surfaces, elevating urban heat emissions and worsening the thermal environment. The urban heat island (UHI) effect has become a prominent reflection of this spatial thermal imbalance. The IPCC's 2023 report highlights that localized warming exacerbates health risks, infrastructure pressure, and social inequality, leading to urban disasters like heatwaves, extreme precipitation, and air pollution.

To address UHI research challenges, the Local Climate Zone (LCZ) classification system was proposed in 2012. This system divides urban and rural surfaces into 17 categories based on physical characteristics, offering a standardized framework for UHI research (STEWART & OKE 2012). LCZ has been increasingly applied in climate simulations (GARDES et al. 2020) and heat island studies (ZHOU et al. 2022).

Traditional landscape pattern research from a two-dimensional perspective has proven that urban green spaces, as an essential component of urban ecosystems, have unique advantages in mitigating UHI and improving environmental comfort (RAYBURG, & NEAVE 2021). Indicators such as coverage (PLAND), density (PD), and shape index (LSI) (MCGARIGAL et al. 2015) significantly affect cooling effects (LIN et al. 2023; YANG et al. 2023). However, cities are inherently three-dimensional, and their temperature regulation mechanisms are not solely determined by two-dimensional surface attributes. Three-dimensional structures, including buildings and vegetation, collectively shape the urban thermal environment (WANG et al.

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2024). Some studies have already demonstrated the correlation between urban three-dimensional features and temperature, such as the impact of building height, floor area ratio (LI & HU 2022, GUAN et al. 2022), and vegetation canopy (CAO et al. 2021) on thermal environment regulation. However, there is still a lack of systematic research on UHI from a three-dimensional urban morphology perspective, and the relevant indicator systems, quantification paths, and explanatory models are not yet unified, making it difficult to effectively support the regulation of urban green spaces for thermal environment control.

Therefore, this study takes Nanjing as the research object, combining the LCZ classification framework, focusing on urban three-dimensional characteristics, especially the temperature association of green space three-dimensional features in different spatial types, to address the following questions:

(1) Does using LCZ classification as a spatial structural unit help in establishing an overall explanatory framework for the relationship between urban three-dimensional features and near-surface air temperature?

(2) What is the relationship between urban three-dimensional features and near-surface air temperature in high-temperature samples?

(3) Are there differences in the association effects between green space three-dimensional features and temperature in different high-temperature LCZ types?

This study aims to enhance the understanding of urban three-dimensional structures (especially green space three-dimensional features) in terms of their temperature response characteristics under high-temperature conditions from the perspective of the LCZ classification. This understanding will provide structural references for climate resilience planning and landscape design driven by cooling demands.

2 Data and Methods

This study focuses on the main urban area of Nanjing, constructing a multi-source data system for meteorological and urban three-dimensional features. The WRF-BEP high-resolution model was used to simulate and, after consistency validation, obtain the 2-meter near-surface air temperature of the city. High-temperature grid subsets were selected, and based on the LCZ classification, urban three-dimensional morphological indicators were further studied. Random forest regression and SHAP methods were used to quantify the marginal contribution of three-dimensional feature indicators to temperature prediction, identify the association patterns between green space three-dimensional features and near-surface air temperature under high-temperature scenarios, and, in the discussion, provide explanatory interpretations of possible process mechanisms, combining existing research.

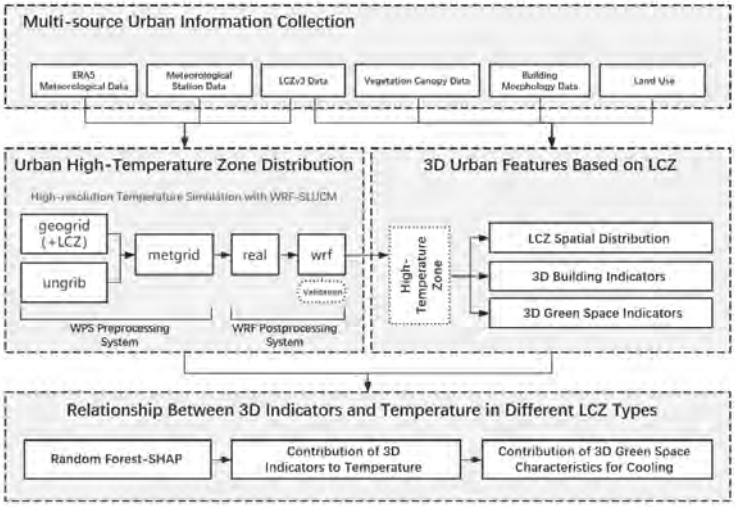

Fig. 1: Research methodology framework

2.1 Study Area

Nanjing (31°14″–32°37″N, 118°22″–119°14″E), located in eastern China along the Yangtze River, has a typical subtropical monsoon climate. As the capital of Jiangsu Prov-ince, it experiences high summer temperatures, especially in July. Following rapid urban-ization, the city's three-dimensional features have become prominent, with the urban heat island (UHI) effect intensifying and expanding, along with stronger canopy UHI intensity (CHEN et al. 2022). Nanjing serves as a typical case for studying UHI and urban three-dimensional characteristics.

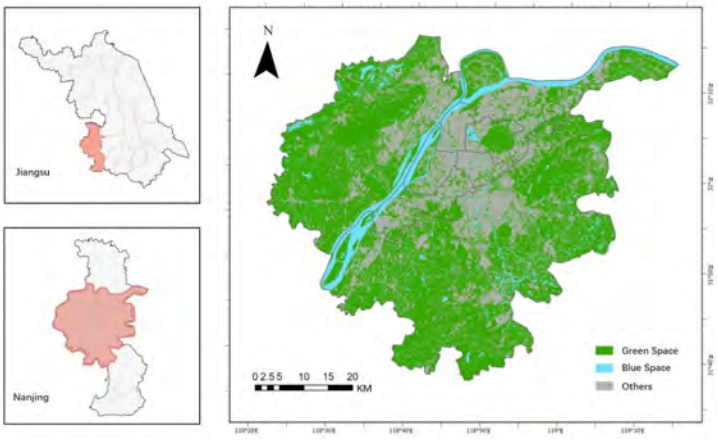

Fig. 2: Study area

2.2 Multi-Source Data Collection for the Urban Area

Multi-source data were used to obtain the distribution of the urban thermal environment, LCZ types, and three-dimensional features at the urban scale. In 2023, the global average temperature increased by 1.45±0.12°C compared to pre-industrial levels, approaching the 1.5°C threshold. The average surface temperature in China in 2023 was 0.84°C higher than the normal level, making it the warmest year since 1901 (CMA Climate Change Centre 2024). Therefore, data for 2023, as a representative year of high temperatures, were collected, with detailed data information provided in Table 1.

Table 1: Data sources and descriptions

Data Type	Data Set Name	Data Source
Meteorological	ERA5	https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download
Meteorological	Nanjing Meteorological Station (58238)	https://rp5.ru/
Urban Morphology	Local Climate Zone (LCZ) v3	https://www.wudapt.org/lcz-maps/
Vegetation Structure	Meta Plant Canopy Height Data (2024)	https://sustainability.atmeta.com/blog/2024/04/22/using-artificial-intelligence-to-map-the-earths-forests/
Land Use	GLC_FCS10 2023	https://doi.org/10.5194/essd-2025-73
Building Morphology	Gaode Map Building Data	https://lbs.amap.com/

To ensure spatial consistency across heterogeneous datasets, all spatial layers were harmonized to the 0.33 km resolution WRF grid, which served as the common analytical unit. This 0.33 km × 0.33 km grid represents the finest spatial resolution (innermost domain) of the WRF simulation and was therefore adopted as the spatial aggregation boundary for all morphological indicators.

All vegetation-related indicators were aggregated to the 333 m analysis grid using zonal statistics. Area-based metrics were derived by converting rasters to binary masks (1 = target class), summing pixel counts per grid cell, and multiplying by pixel area. Height-based metrics (mean and standard deviation) were computed using zonal MEAN and STD after masking non-vegetated pixels as NoData. Raster alignment was ensured through snap raster and consistent cell size settings.

Building footprint and height data were spatially intersected with the WRF grid. Height-related indicators and volume-based indicators were calculated by summarizing building attributes within each grid cell. This ensured that all three-dimensional indicators were derived consistently within the same spatial unit.

2.3 Quantifying Urban Three-Dimensional Features Based on LCZ Classification

Table 2: Three-dimensional morphological indicator system constructed in the study

Category	Indicator Name	English Name	Formula
Green Space	TH	Plant Average Height	$\mathrm{TH} = \frac{\sum H_i}{n}$
	THstd	Plant Height Standard Deviation	$TH_{std} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_i - \bar{H})^2}$
	TVD	Plant Volume Density	$\mathrm{TVD} = \frac{\sum(H_i \times A_i)}{A_{\mathrm{grid}}}$
	TR	Plant Three-Dimensional Structure Proportion	$\mathrm{TR} = \frac{A_{\mathrm{tree}}}{A_{\mathrm{grid}}}$
	TGR	Plant Three-Dimensional Structure to Green Space Ratio	$\mathrm{TGR} = \frac{A_{\mathrm{tree}}}{A_{\mathrm{green}}}$
	BTVR	Building to Plant Volume Ratio	$\mathrm{BTVR} = \frac{\sum(H_i \times A_i)}{\sum(h_j \times a_j)}$
Building	BH	Building Average Height	$\mathrm{BH} = \frac{\sum H_i}{n}$
	BHmax	Building Maximum Height	$\mathrm{BH}_{\mathrm{max}} = max(H_i)$
	BHmin	Building Minimum Height	$\mathrm{BH}_{\mathrm{min}} = min(H_i)$
	BHstd	Building Height Standard Deviation	$BH_{std} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_i - \bar{H})^2}$
	BVD	Building Volume Density	$\mathrm{BVD} = \frac{\sum(H_i \times A_i)}{A_{\mathrm{grid}}}$

Based on the temperature distribution, and to systematically depict the relationship between urban three-dimensional features and temperature, this study introduces the Local Climate Zone (LCZ) classification (DEMUZERE et al. 2022, STEWART & OKE 2012) as the foundational framework for categorizing urban three-dimensional morphological types. LCZ classifies urban areas into 10 building types (1-10) and 7 natural types (A-G) based on factors

such as building density, height, vegetation, and land use. This classification not only has inherent advantages in defining three-dimensional spatial structures but is also widely used in urban heat island research.

Building on the LCZ classification, a three-dimensional morphological indicator system for buildings and green spaces is developed to further characterize the three-dimensional spatial features within each LCZ type. The focus is on examining the contribution of various indicators to temperature within different LCZ types, particularly the temperature impact of green space three-dimensional features in different LCZ categories.

2.4 WRF Model for Urban High-Temperature Area Distribution

Most studies use remote sensing-based land surface temperature (LST) inversion methods to calculate surface temperatures, but these are limited by temporal resolution and differ from actual urban climate conditions. The Weather Research and Forecasting (WRF) model (TAPIADOR et al. 2020) effectively reproduces the spatial and temporal variations of near-surface temperatures in urban areas (HUANG et al. 2025), capturing processes influenced by urban three-dimensional structures like ventilation, radiation balance, water vapor exchange, and surface roughness, enhancing the physical explanation of thermal environments.

For the simulation, data from Nanjing meteorological stations (June-August 2023) was used, focusing on the high-temperature period from July 8-14, 2023. ERA5 reanalysis data provided initial and boundary conditions, with static geographic data sourced from WPS multi-source datasets. The simulation used a four-level, two-way nested grid (resolutions of 9 km, 3 km, 1 km, and 0.33 km), refining from regional to urban-scale resolution, covering Nanjing and surrounding areas. At the highest resolution (0.33 km), the WRF model was coupled with a multi-layer urban canopy scheme, the Building Effect Parameterization (BEP), to simulate urban thermal processes, incorporating LCZ data via the w2w tool (ZHENG et al. 2024).

The WRF model's recommended configuration, including microphysics, radiation, boundary layer, and land surface process modules, was used. Simulated data for wind speed, direction, and temperature at 2 meters were processed using a high-performance computing cluster. Verification against Nanjing station temperature data and remote sensing-derived LST data showed that the simulated temperature trends matched observed results, with reasonable error margins, supporting further spatial analysis of high-temperature areas.

2.5 Random Forest – SHAP Explanation Method

The minimum WRF grid resolution (0.33 km) was adopted as the analytical unit, integrating three-dimensional morphological indicators with near-surface air temperature. After data cleaning, a random forest regression model (RF) was built using 27,787 samples to model the nonlinear relationship between urban three-dimensional structure and temperature. RF is suitable for complex morphology–climate interactions due to its nonlinear fitting ability and robustness to multicollinearity (OUKAWA et al. 2022).

The dataset was randomly divided into training and test sets at a ratio of 80:20 (random_state = 42). The RandomForestRegressor was implemented in Python (scikit-learn) with the following hyperparameters: n_estimators = 500, max_depth = 10, min_samples_leaf = 15, max_features = 0.7, bootstrap = True, and oob_score = True (n_jobs = −1). Tree depth was limited and a relatively large minimum leaf size was specified to suppress the influence of

extreme grid samples and enhance model stability. The number of trees was increased to reduce variance introduced by random sampling and to improve the stability of the explanatory results.

After global modeling, the top 10% of grid cells with the highest simulated temperatures were extracted to represent areas with significant cooling demand. SHAP (SHapley Additive exPlanations) values were computed using shap.TreeExplainer for the trained RF model. Feature importance was quantified as the mean absolute SHAP value (mean(|SHAP|)), and dependence plots were generated without interaction terms (interaction_index = None). SHAP was used solely for post-hoc interpretation and did not affect model training or evaluation.

To evaluate model robustness and generalization performance, a multi-level validation strategy was adopted, including out-of-bag (OOB) estimation, independent test set validation, and five-fold cross-validation. Model performance was assessed using the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE). A baseline reference model was also introduced to avoid overinterpreting absolute error magnitudes and to more clearly assess the explanatory contribution of three-dimensional morphological indicators to temperature variation.

During the writing of this paper, part of the content organization and text optimization was assisted by OpenAI's ChatGPT (version GPT-5.2). ChatGPT provided assistance in language refinement only; all research results, analysis, and conclusions were derived from actual data processing and independently verified by the authors.

3 Result

3.1 Distribution Characteristics of LCZ Categories in High-Temperature Areas

Based on the WRF simulation results, daily statistics show that, except for July 13, 2023, the other days had significant high-temperature distributions, with average temperatures exceeding 30°C. On July 12, the highest temperature reached 34.05°C. From July 8 to 14, the 2-meter near-surface average temperature in Nanjing ranged from 28.17°C to 31.61°C, with an overall average of 30.20°C. The top 10% of the highest temperature areas were extracted, and the results show that the high-temperature regions are concentrated in the southern part of the Yangtze River, the northwest of the Ning-Zhen Mountains, the west-ern part of Qixia District, parts of Xuanwu District surrounding Zijin Mountain, the north-ern part of Jiangning District, and the northern part of Laoshan in Pukou District. The five LCZ categories with the largest coverage of high-temperature areas (accounting for 86%) were LCZ 8, LCZ 6, LCZ D, LCZ 9, and LCZ 5.

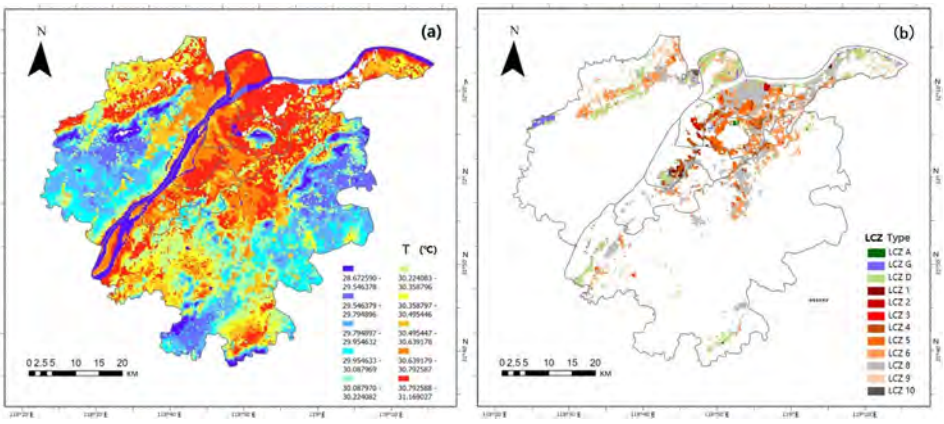

Fig. 3: (a) Temperature distribution in the study area; (b) LCZ type distribution in high-temperature areas

3.2 Distribution Characteristics of Urban Three-Dimensional Morphology in High-Temperature LCZ Categories

The spatial distribution characteristics of green space and building indicators in high-temperature areas were analyzed from two dimensions: green space indicators and building indicators.

In terms of green space indicators, TH, TVD, and TR exhibit similar spatial patterns, with high values mainly concentrated in LCZ 8, 5, and 6. TGR shows high values concentrated in LCZ 6, D, and 8, particularly near the mountains. BTVR, on the other hand, exhibits the opposite trend to the green space indicators, with higher values clearly found in LCZ 1-5. This indicates a building-dominated, vegetation-scarce structural state, suggesting that buildings have a greater advantage, while vegetation volume is relatively insufficient. In the model interpretation, this is more likely to occur alongside higher temperature predictions, thus providing a structural explanation for the high-temperature spatial pattern.

Building indicators present a more complex spatial distribution. High values of BHstd are mainly distributed in the high-development areas south of the Yangtze River. High values of BHmax and BHmin are distributed in different regions. Building volume density is highest along the southern side of the Yangtze River. There are still significant spatial differences between high-temperature LCZ categories and three-dimensional morphological features, providing a structural basis for subsequent thermal environment studies.

3.3 Contribution of Three-Dimensional Morphological Indicators in High-Temperature LCZ Types

This section first provides the overall explanatory framework for the contribution of three-dimensional indicators to temperature differences at the global scale. Then, based on the same model, high-temperature samples are grouped and sliced by LCZ to identify the green space three-dimensional indicators that are more frequently associated with lower temperature predictions and have landscape intervention potential in different spatial types.

The random forest model trained on the entire sample (n≈27,800) shows a coefficient of determination of approximately 0.31 for both the independent test set and out-of-bag (OOB) samples, and the results of five-fold cross-validation are stable (R^2≈0.31, standard deviation ≈ 0.01), indicating that the model can robustly depict the nonlinear relationship between three-dimensional morphological indicators and near-surface temperatures without pursuing high fit precision. Based on this model, the top 10% of the highest near-surface temperature grid cells were selected as the high-temperature subset (n≈2,800), and five types of spatial units (LCZ5, LCZ6, LCZ8, LCZ9, and LCZD) were extracted for conditional explanation analysis (total n≈2,400).

(1) Global RF-SHAP Results

The global RF–SHAP results show that temperature differences are primarily driven by building three-dimensional features: BVD has the highest contribution, followed by BH and BHmax, indicating that the volume and height characteristics of the built environment are the main sources of spatial temperature variation at the large scale (Figure 4). In this context, green space-related indicators still show recognizable contributions, with TGR ranking highest among the green space variables, and TR also maintaining a certain level of importance. The beeswarm plot further shows that higher values of BVD/BH/BHmax are more likely to correspond to positive SHAP contributions, while higher values of TGR/TR are more likely to correspond to negative SHAP contributions. Meanwhile, higher values of BTVR are more likely to result in positive contributions. Overall, the global results characterize the background differences dominated by buildings and the supplementary explanation of green space factors, providing a reference for subsequent group slicing and indicator comparison in high-temperature samples based on LCZ.

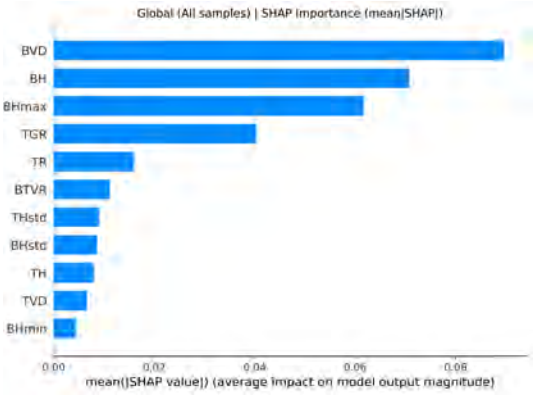

Fig. 4:
Global SHAP feature importance

(2) LCZ Grouping Results for High-Temperature Samples

The top 10% temperature areas from the WRF results were selected for analysis. Using the LCZ classification system, the relative importance of each indicator in the main high-temperature LCZ types (LCZ 5, 6, 8, 9, D) was ranked and analyzed based on RF-SHAP. The results indicate that, in an environment primarily influenced by buildings, the influence of green space three-dimensional variables varies across different LCZ types, but the overall trend still shows a noticeable commonality (Figure 5).

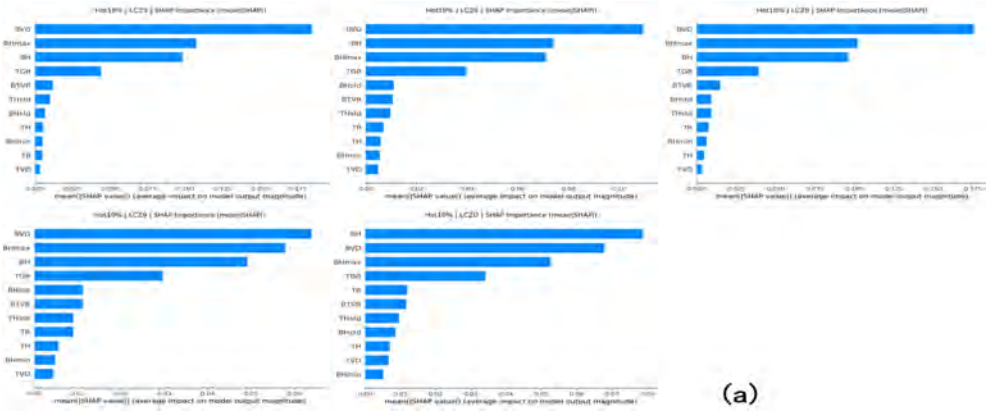

Fig. 5: (a) SHAP Feature Importance by LCZ Type

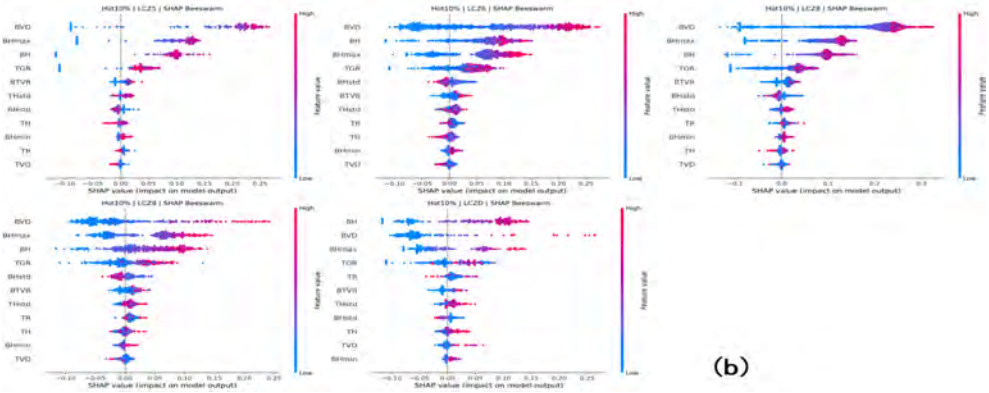

Fig. 5: (b) SHAP summary plot by LCZ type

When viewed by type, the importance rankings of variables in each LCZ reflect the supplementary explanation of temperature differences within the space by green space three-dimensional features, making these variables more meaningful for landscape interventions. In LCZ5, green space indicators are mainly represented by TGR, with BTVR and THstd ranking higher among green space indicators. In LCZ6, the ranking is similar to LCZ5, with TGR remaining high, while the contributions of BTVR and THstd are significantly reduced. In LCZ8, TGR constitutes the main green space indicator contribution, with BTVR being of secondary importance. In LCZ9, TGR's importance significantly increases compared to the three major building indicators, also highlighting the secondary importance of green space indicators like BTVR, THstd, and TR. In LCZ D, apart from building-related indicators, TGR and TR maintain high importance, suggesting that differences in green space structures in natural background high-temperature samples are still an important explanatory source. Notably, TGR maintains high importance across all LCZs, while the roles of BTVR, THstd, TR, and other indicators vary with the LCZ type, further indicating that the temperature association effects of green space three-dimensional structures are context-dependent.

3.4 Specific Temperature Contribution of Green Space Three-Dimensional Indicators in Different LCZ Types

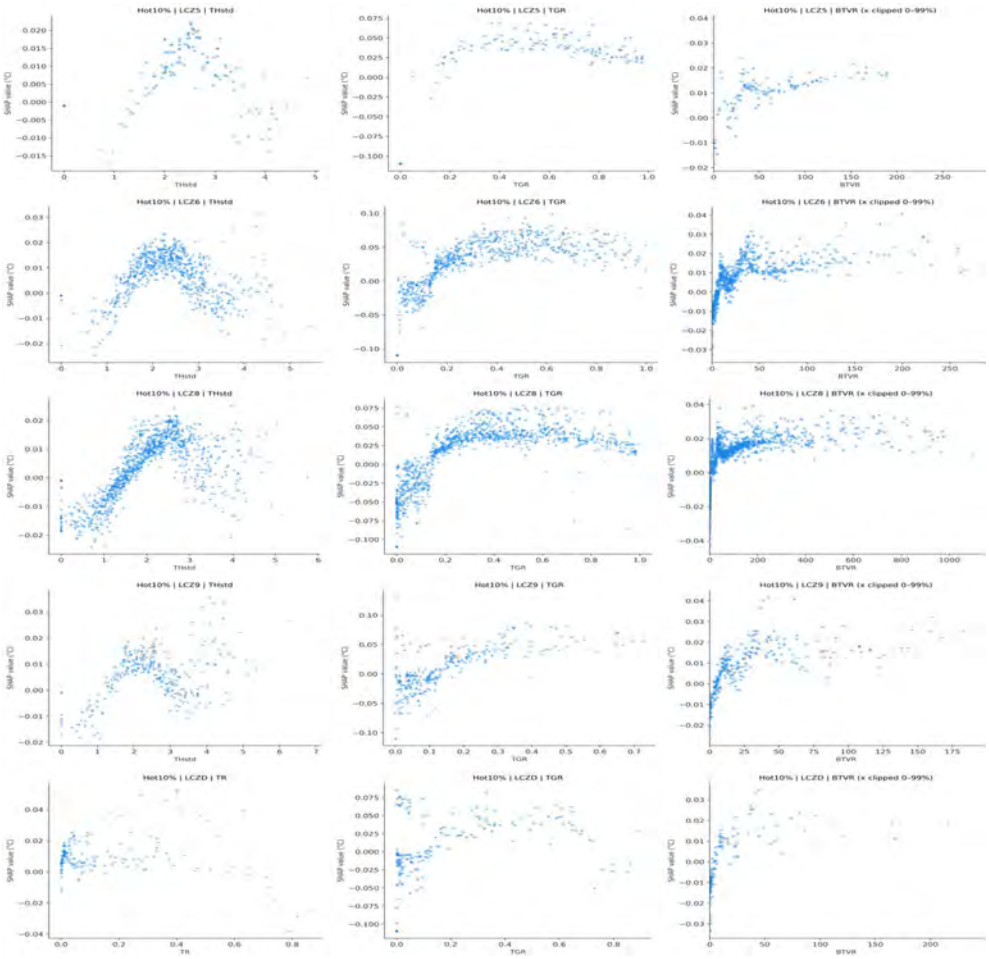

Fig. 6: Univariate analysis of important indicators in high-temperature LCZ

This section characterizes the impact of green space three-dimensional indicators on temperature differences in high-temperature samples using SHAP results from the global RF model. SHAP dependence scatter plots (Figure 6) are drawn for typical LCZ types, highlighting green space indicators of higher importance and landscape intervention significance. The x-axis represents indicator values, and the y-axis shows the indicator's marginal contribution to the model's temperature output (SHAP value), with positive/negative values indicating warming/cooling contributions. BTVR's x-axis is clipped by quantiles to avoid long-tail compression for visualization.

In LCZ 5, TGR shows a nonlinear "rising then flattening" pattern. BTVR has a positive relationship with SHAP, increasing quickly in the low range and flattening. THstd has an "inverted U-shape," with higher positive SHAP in the middle range and lower values near zero or negative SHAP, reflecting varying response amplitudes.

In LCZ 6, TGR has concentrated negative SHAP in the low range, turning positive in the middle range. BTVR follows a similar pattern, with rapid changes in the low range and a flatter response at higher values. THstd shows more prominent positive responses in the middle range.

In LCZ 8, BTVR's response is highly segmented, with negative SHAP in the low range and positive SHAP in the middle range. TGR shows a negative-to-positive SHAP transition. THstd shows varied responses at different value levels.

In LCZ 9, BTVR contributes monotonically, with more sensitivity in the low range. TGR's SHAP increases with value, suggesting its association with a warming background. THstd follows an "inverted U-shape," with higher values showing more dispersion.

In LCZ D, with a smaller sample size, BTVR has negative or near-zero SHAP in the low range, becoming positive as it increases. TGR shows both positive and negative SHAP at different value ranges, and TR's positive values decrease at higher TR, requiring further confirmation.

4 Discussion

4.1 Explanatory Framework of Green Space Three-Dimensional Features Based on Cooling Demand under LCZ Constraints

This study analyzes cooling demand under urban high-temperature scenarios, using the LCZ classification framework to explain the role of green space three-dimensional features. Unlike traditional two-dimensional perspectives, it emphasizes how three-dimensional features of green spaces contribute to temperature differences in various spatial contexts under high near-surface temperatures, exploring their cooling potential. Here, "cooling effect" refers to three-dimensional features stably associated with lower temperatures in high-temperature conditions, not a direct causal reduction.

RF–SHAP results show that building volume and height dominate temperature differences, highlighting the built environment's foundational role in urban thermal environments. The introduction of LCZ classification reveals that, even in areas where buildings primarily affect the thermal environment, detailed green space three-dimensional features can still explain temperature variations within the same LCZ type. By defining these features within the LCZ framework, the temperature association effects of green space can be more specifically linked to LCZ categories.

In this study, LCZ serves not just as an urban spatial label but as a structural constraint, defining the context in which green space features can play a role. This approach provides a more targeted framework for interpreting green space three-dimensional features in relation to cooling demand.

4.2 Green Space Three-Dimensional Features and Cooling Contribution in Different High-Temperature LCZ Types

In terms of indicator composition, green space variables can be grouped into three-dimensional coverage indicators (e. g., plant three-dimensional structure to green space ratio, TGR; tree canopy coverage, TR) and structural indicators (e. g., building-to-vegetation volume ratio, BTVR; plant height standard deviation, THstd). In high-temperature samples, these indicators show both differential stability and LCZ-dependent variation.

TGR maintains consistently high importance across all LCZ types, suggesting that tree canopy-related structural volume is a fundamental factor associated with near-surface temperature variation. This finding complements existing studies on two- and three-dimensional green space structures and their thermal effects (CILEK et al. 2024, HAN et al. 2023, TANOORI et al. 2024). However, the strength and direction of SHAP responses vary across LCZ backgrounds.

In building-dominated LCZs (e. g., LCZ5 and LCZ8), green space indicators provide supplementary explanations for temperature differences within similar built contexts. The SHAP dependence patterns of TGR and TR show clear nonlinearity, with more concentrated negative SHAP values in specific value ranges, indicating that vegetation structure is associated with lower temperature predictions only under certain structural conditions.

In LCZ6 and LCZ9, TGR remains important but exhibits segmented or plateau-type responses. BTVR and THstd also display nonlinear patterns, such as sensitivity in lower value ranges or inverted U-shaped tendencies, suggesting that vegetation–building volume balance and height heterogeneity contribute differently depending on spatial context.

In natural LCZs (e. g., LCZD), SHAP distributions are more dispersed, though TGR and TR still maintain relatively high importance. The mixed positive and negative SHAP values indicate that vegetation density alone does not uniformly correspond to cooling but interacts with broader morphological conditions.

Overall, the contribution of green space three-dimensional structure to temperature variation is context-dependent rather than uniform across LCZ types. This implies that green space design strategies should avoid universal thresholds and instead account for nonlinear responses and spatial background differences within specific LCZ contexts.

4.3 Study Limitations and Future Prospects

Due to the research scope and methodological framework, several limitations remain.

(1) This study focuses on the top 10% of grid cells with the highest simulated temperatures, emphasizing areas with the strongest cooling demand. While this approach highlights structural differences under extreme heat conditions, the conclusions are mainly applicable to high-temperature contexts. Temperature responses in moderate or low-temperature scenarios and across seasonal variations were not systematically examined. Future research could incorporate multi-quantile temperature ranges or comparative heat-risk levels to test the stability and transferability of structural indicators under different climatic conditions.

(2) The three-dimensional indicator system primarily reflects macro-scale structural characteristics and does not fully address design-controllable factors at finer spatial scales. Variables such as plant and building volume, density, and height were considered, but site-level

strategies – such as species selection, canopy layering, or water feature integration – were not explicitly evaluated. Future studies combining high-resolution remote sensing, field measurements, and microclimate simulations could further refine these structural indicators and improve their applicability to landscape design practice.

5 Conclusion

Centered on cooling demand under high-temperature conditions, this study examines the relationship between urban three-dimensional morphology – particularly green space structure – and 2 m near-surface air temperature within the LCZ framework. Based on a global random forest model and LCZ-based grouping of high-temperature samples, the following conclusions are drawn.

First, using LCZ as a structural boundary clarifies the differentiated associations between green space three-dimensional indicators and temperature across urban morphology types. Compared with undifferentiated analyses, this framework better distinguishes background-dominant built factors from green space variables with potential regulatory relevance.

Second, temperature variation in high-temperature samples is primarily driven by built environment structure. However, green space three-dimensional indicators show stable yet context-dependent effects across LCZ types. Tree and shrub structural volume (e. g., TGR) maintains consistently high importance with nonlinear responses, while BTVR and THstd exhibit LCZ-specific and segmented patterns. These findings suggest that no universal optimal threshold exists; instead, temperature associations must be interpreted within specific morphological contexts.

Finally, the results support the LCZ framework as a bridge between urban climate analysis and spatial design. Three-dimensional green space indicators can serve as structural references for heat-risk-oriented planning. As RF–SHAP results represent statistical associations rather than causal mechanisms, the conclusions should be understood as context-specific structural insights rather than universal design standards. Future research combining field measurements and microclimate simulations can further validate these findings at finer spatial scales.

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Quantifying the Relationship Between Street-Level Solar Radiation and Human Perception Using Street View Imagery: Evidence from the Central Urban Area of Shenzhen

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Abstract: Solar exposure influences pedestrians' thermal comfort and visual experience by shaping light-shadow conditions and thermal exposure and constitutes a key environmental factor in microclimate regulation and human-centred spatial design in high-density cities. Taking the central urban area of Shenzhen as the study area, this study develops a street-scale solar radiation estimation approach by integrating Baidu Street View (BSV) panoramic imagery with a solar geometry model, and further combines it with a deep learning-based streetscape perception prediction model to systematically examine the spatial patterns of solar radiation and its coupling relationship with street-level visual perception.

The results indicate pronounced spatial heterogeneity in street-scale solar radiation across Shenzhen's central area, characterized by a gradient of higher radiation in peripheral areas and lower radiation in the urban core. Street spatial morphology plays a significant moderating role in solar exposure: expanded sky view substantially enhances direct solar radiation, whereas building shading and street greenery effectively reduce solar exposure levels. Statistical analyses reveal a significant negative correlation between solar radiation and composite streetscape perception scores ($r = -0.74$, $p < 0.001$), with a clear non-linear pattern. Streets with moderate radiation levels are more likely to receive higher perceptual evaluations, while both excessively high and excessively low radiation environments are unfavourable for positive streetscape experiences, indicating a design-relevant "perceptual comfort window" at the street scale. Further results demonstrate that greenery exerts an important moderating effect in the radiation-perception relationship, not only by mitigating solar exposure but also by enhancing visual and psychological comfort.

Methodologically, this study integrates street-view-image-driven solar radiation estimation with perception prediction models, enabling high-resolution quantification of radiation-perception relationships at the street scale. The findings provide a replicable technical pathway for understanding the interactions between street morphology, solar exposure, and human-centred perception in subtropical high-density cities, and offer quantitative evidence to inform street shading design, greening strategies, and climate-adaptive urban renewal.

Keywords: Solar radiation, baidu street view, street canyons, urban spatial perception, microclimate regulation

1 Introduction

Under the dual pressures of rapid urbanization and global climate change, the creation of urban public spaces that are both climate-adaptive and thermally comfortable has become a central concern in contemporary urban planning and design. At the street scale, solar radiation is a key factor influencing surface energy balance, street-level microclimate, and the pedestrian thermal environment (AZEGAMI et al. 2023). Beyond its physical thermal effects, solar radiation in street spaces also profoundly shapes pedestrians' thermal perception, visual

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experience, and choices of outdoor activities through visual cues such as variations in brightness and shadow patterns (LIU & HANG 2025, DONG et al. 2025, SANG et al. 2025). However, existing studies on the urban thermal environment have largely focused on physiological exposure and thermal comfort indices, while relatively little attention has been paid to how solar radiation is "perceived" within street spaces and translated into subjective experience. This gap limits the applicability of current research findings to street design and fine-grained environmental regulation.

In high-density urban environments, the coupled effects of street geometry, vegetation structure, and road orientation give rise to pronounced spatial heterogeneity in solar exposure distribution (TODD 2023, AZEGAMI et al. 2023). Previous studies have shown that factors such as street orientation, height-to-width ratio (H/W), tree canopy coverage, and surface materials can substantially regulate solar radiation levels within street canyons by altering sunshine duration, shading patterns, and radiation intensity (PARK et al. 2015, WANG et al. 2024, SANG et al. 2025). At the same time, the effects of solar radiation exhibit marked seasonal variability: strong radiation in summer tends to induce thermal discomfort, whereas winter or moderate radiation may enhance outdoor comfort by improving thermal and lighting conditions (LI & RATTI 2019a, GUO et al. 2025). These findings suggest that characterizing solar radiation solely from a physical perspective is insufficient, and that its perceptual implications at the pedestrian scale warrant further investigation.

Despite the growing body of research on urban solar radiation, methodological and scale-related limitations remain. On the one hand, meteorological stations are sparsely distributed and are typically located in open areas, making it difficult to capture radiation variability within street spaces shaped by the combined effects of buildings and vegetation (WU et al. 2007, PARK et al. 2015). On the other hand, radiation simulations based on high-resolution three-dimensional urban models can provide detailed results, but they entail high data and computational costs and often struggle to accurately represent the vertical structure of street tree canopies and their seasonally varying shading effects (TOMASI et al. 2024, Wang et al. 2026). In addition, conventional remote sensing approaches primarily rely on overhead perspectives, which are poorly suited to capturing the pedestrian visual environment, thereby constraining their ability to explain the relationship between light-shadow conditions and subjective perception (ZHANG et al. 2019).

In recent years, the widespread use of street view imagery (e. g. Google Street View and Baidu Street View) has provided a scalable, pedestrian-perspective approach for street-scale environmental research (ZHOU et al. 2022, CHEN et al. 2025). Street view images record sky openness, building interfaces, and tree canopy occlusion from a first-person perspective, offering an important data basis for estimating pedestrian-level solar radiation exposure and its perceptual characteristics (CARRASCO-HERNANDEZ et al. 2015, LI & RATTI, 2019a, 2019b, WANG et al. 2024). When combined with semantic segmentation and deep learning-based perception models, these data enable the quantitative assessment of multiple perceptual dimensions – such as perceived safety, vibrancy, and aesthetic quality – at the city scale, thereby creating new opportunities to explore the coupling between solar radiation, spatial morphology, and human perception (ZHANG et al. 2018).

Nevertheless, much of the existing literature has focused primarily on street orientation or local morphological characteristics, with relatively limited systematic differentiation between road functional types (such as expressways, arterial roads, secondary roads, local

streets, and non-motorized streets). Road types differ markedly in terms of spatial openness, greening configuration, and usage patterns, which may lead to distinct solar radiation exposure characteristics and perceptual response mechanisms. Moreover, an increasing number of studies suggest that the relationship between solar radiation and perceptual indicators may not be strictly linear but instead characterized by threshold effects or "comfort ranges". This feature has important implications for fine-grained street design and policy formulation (CHEN et al. 2024, DONG et al. 2025, TOMASI et al. 2024).

Against this background, the present study focuses on the central urban area of Shenzhen and proposes a road-segment-based analytical framework to investigate the coupling between urban form, solar exposure, and street perception. Using large-scale Baidu Street View imagery, panoramic images are transformed into fisheye images and combined with solar trajectory geometry to estimate solar exposure. At the same time, deep learning-based semantic segmentation and perception prediction models are employed to extract multi-dimensional street perception indicators, enabling a spatially explicit coupling analysis between solar radiation and pedestrian perception (ZHANG et al. 2018, LI & RATTI 2019b). Rather than replacing traditional microclimate simulations centred on physiological thermal indices, this approach complements them from a perceptual perspective, providing a highly reproducible and scalable pathway for street-scale environmental assessment.

The specific objectives of this study are to: (1) characterize the spatial distribution of solar exposure across different road types in Shenzhen under summer conditions; (2) quantitatively analyse the statistical relationship between solar radiation and overall street perception, identifying potential non-linearities and threshold effects; and (3) propose microclimate optimization strategies and human-centred design implications tailored to different road types.

2 Methodology

2.1 Study Area and Street View Data

The study focuses on the central urban area of Shenzhen, China, including Nanshan, Futian, and Luohu districts (Figure 1). Shenzhen features a dense built environment and complex street morphology, with pronounced street canyon effects and strong spatial heterogeneity of solar radiation at the pedestrian scale (GONG et al. 2019). The subtropical climate and high solar altitude from May to October make this period suitable for capturing peak pedestrian heat exposure while minimizing seasonal variation (LI & RATTI 2019a).

Street network data were obtained from OpenStreetMap, and sampling points were generated at 100 m intervals along road centrelines, yielding 71,544 locations. Panoramic street view metadata were retrieved via the Baidu Street View (BSV) API, including panorama IDs, acquisition dates, and camera orientation (Drivedir, DD). After seasonal filtering, deduplication, and quality control, 28,781 panoramic images were retained (Figure 2).

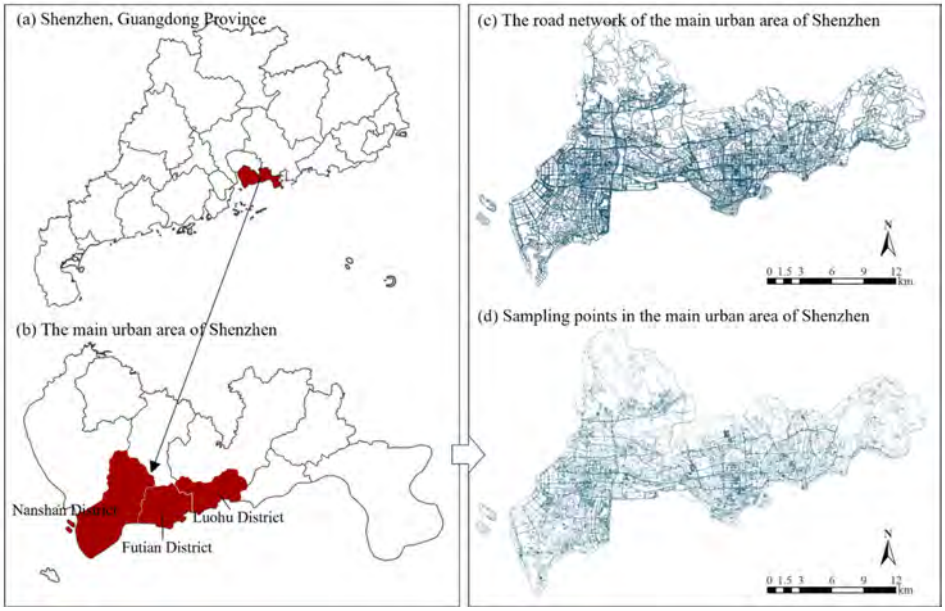

Fig. 1: Research scope illustration: (a) Shenzhen, Guangdong Province (b) The main urban area of Shenzhen (c) The road network of the main urban area of Shenzhen (d) Sampling points in the main urban area of Shenzhen

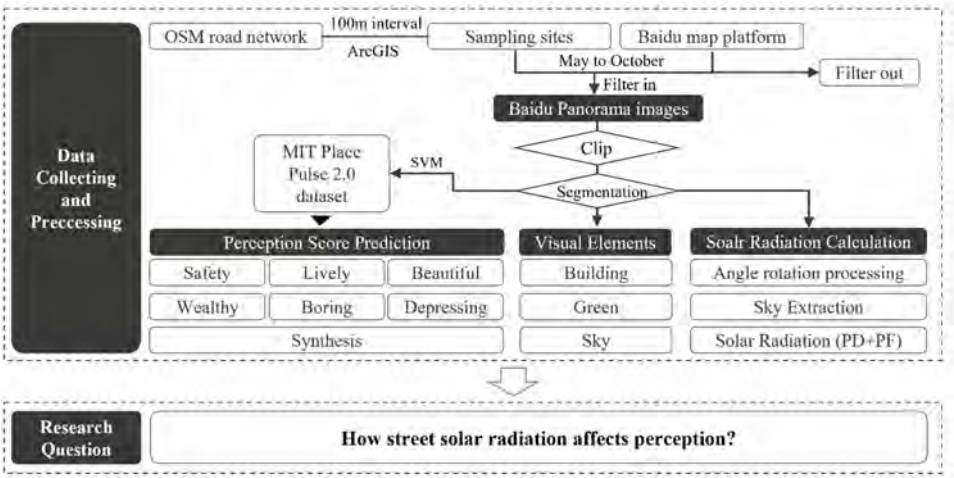

Fig. 2: Technical route

2.2 Solar Radiation Estimation and Perceptual Assessment

BSV panoramas were first transformed into hemispherical fisheye images using an equidistant azimuthal projection to represent sky visibility and street obstructions (MATZARAKIS

2010) (Figure 3). Images were azimuth-corrected using camera orientation metadata for consistent north alignment (LI & RATTI 2019a).

Semantic segmentation was applied to classify pixels as sky, buildings, or vegetation, allowing the quantification of potential solar-accessible areas at the street scale (Zhou et al., 2018). Solar trajectories were overlaid to assess direct and diffuse radiation accessibility across time. Relative radiation differences were used to reduce uncertainties from varying atmospheric conditions, calibrated with ERA5-Land data (MUÑOZ SABATER 2019), producing an average street-scale solar exposure indicator (Rc) for May–October (Figure 4).

Street-level perceptual indicators were derived using a deep learning framework trained on the MIT Place Pulse 2.0 dataset. Each image received continuous scores on six dimensions: Safe, Lively, Beautiful, Wealthy, Boring, and Depressing (ZHANG et al. 2018). These scores were combined into a comprehensive perception index using an equal-weight strategy, with negative dimensions inversely coded.

By aligning solar radiation exposure and perceptual indicators at the road-unit scale, the dataset provides a basis for analyzing spatial variations in radiation-perception relationships across different street types.

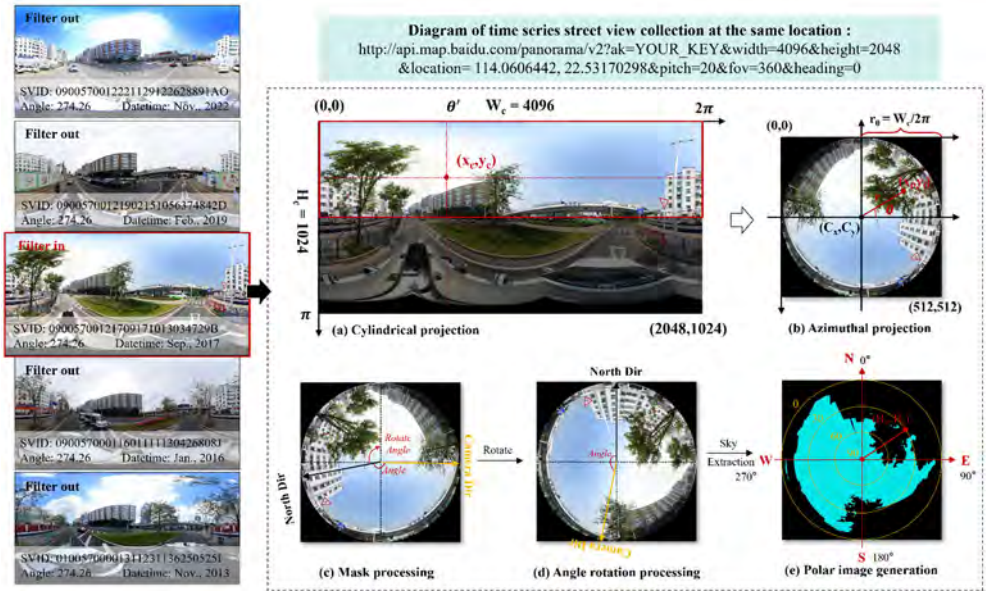

Fig. 3: Examples of street view image screening and collection: (a) Filter summer street view data (b) The tiles of a BSV panorama and two tiled images

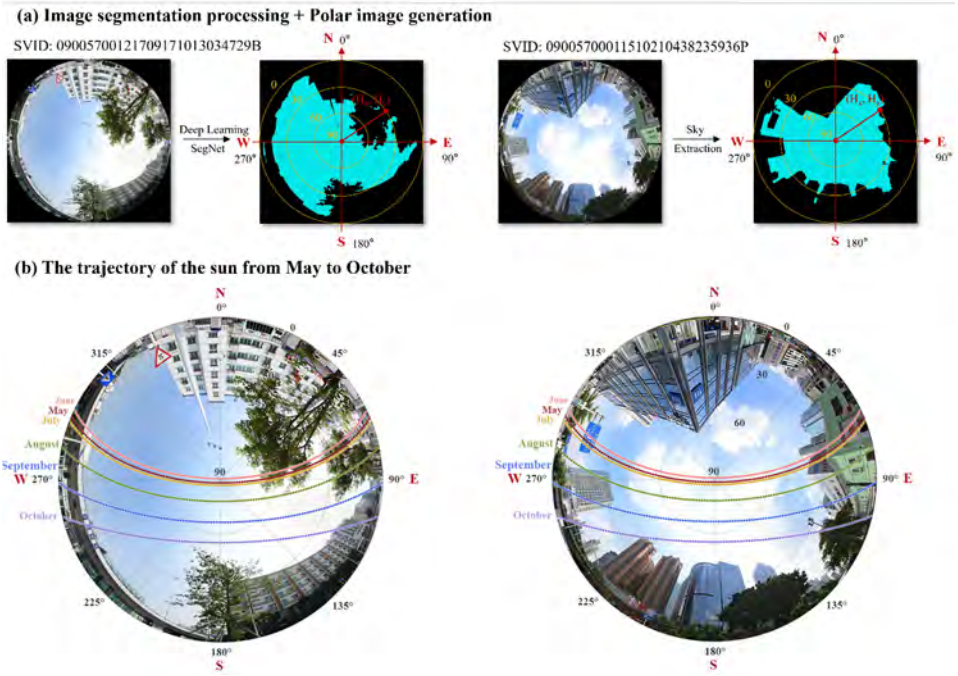

Fig. 4: Solar radiation trajectory tracking display based on fisheye images

3 Results

Based on BSV fisheye images overlaid with solar trajectory calculations to derive street-scale solar radiation exposure indicators, and combined with street visual elements (Building, Sky, Green) as well as deep-learning-based perceptual predictions, this study systematically characterizes the spatial distribution of street-scale solar radiation in the main urban area of Shenzhen and analyses its statistical relationship with street perception.

3.1 Street-Scale Spatial Patterns of Solar Radiation

Street-scale solar radiation exposure levels exhibit significant spatial variation across the study area, displaying a clear “higher at the periphery, lower in the centre” gradient pattern (Figure 5-6). Coastal peripheral areas show higher radiation levels, whereas the dense central built-up areas experience comparatively lower radiation exposure.

Correlation analysis indicates that sky view factor is significantly positively correlated with solar radiation, while greenery ratio and building proportion are both significantly negatively correlated with solar radiation ($p < 0.001$). Systematic differences in radiation levels are observed across varying proportions of visual elements.

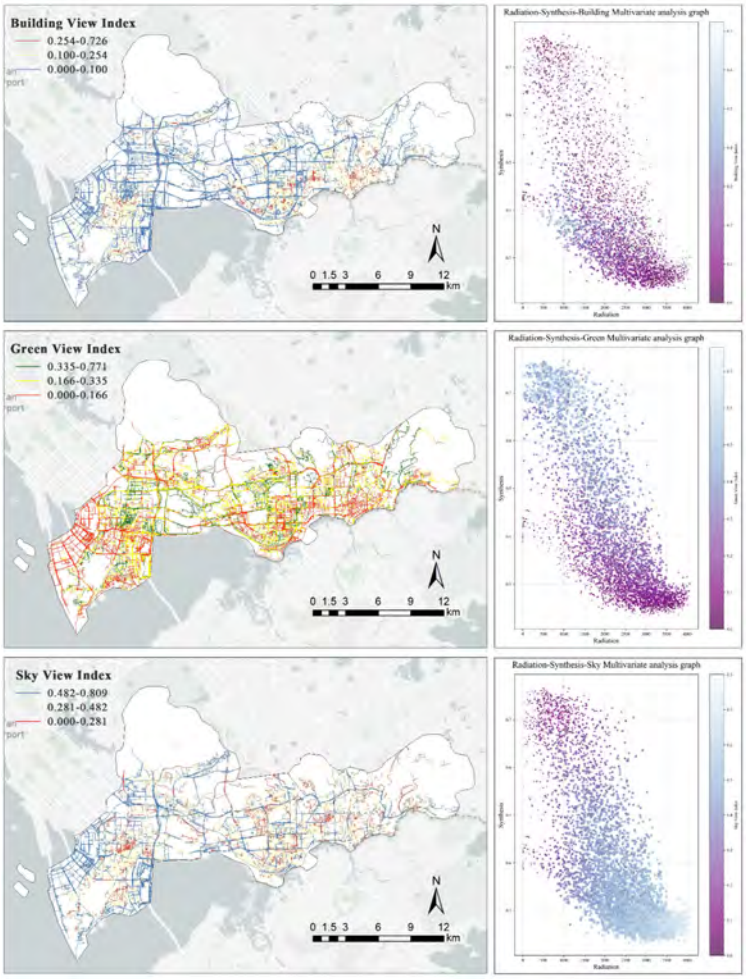

Fig. 5: The spatial distribution of different solar radiation and visual element proportions

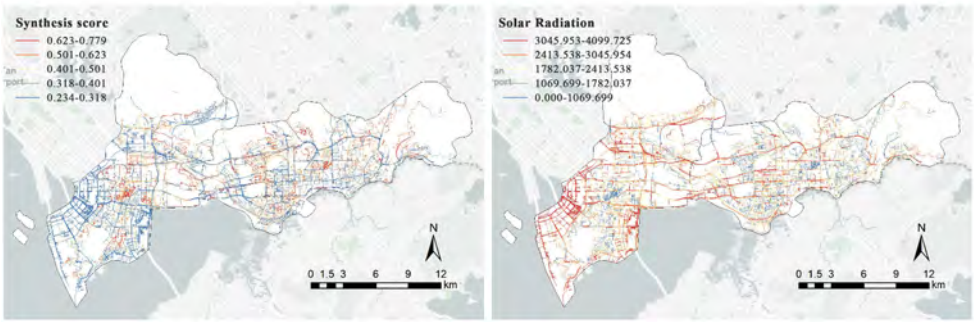

Fig. 6: Analysis of cold and hot spots based on comprehensive perception and solar radiation

3.2 Coupling Between Solar Radiation and Street Perception

The proportion of solar radiation is significantly negatively correlated with the comprehensive perception score (Synthesis) ($r = -0.74$, $p < 0.001$) (Fig. 7). Interval-based analysis shows that when radiation ratios range between 0.35 and 0.55, comprehensive perception scores are relatively high. By contrast, when radiation exceeds 0.65 or falls below 0.25, perceptual scores decline markedly.

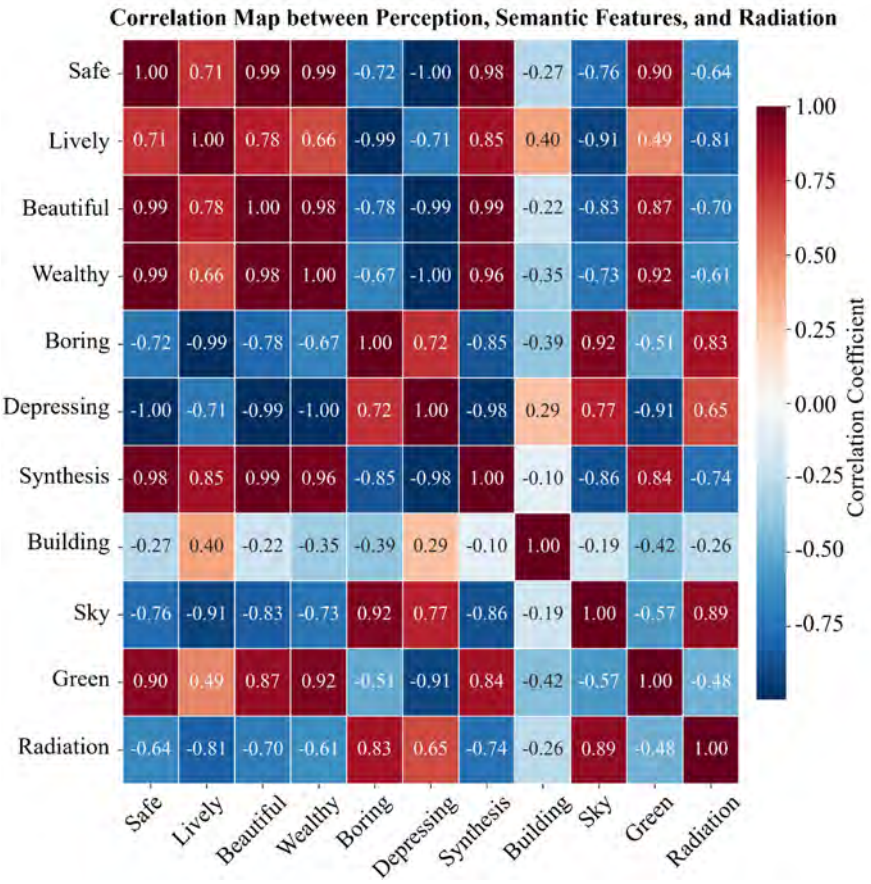

Fig. 7: Correlation analysis of perceptual scores, visual elements and solar radiation levels

Multivariate analysis further reveals the significant moderating role of greenery in the relationship between solar radiation and street perception. The multivariate bubble plot in Figure 5 shows that high perceptual scores are primarily concentrated in street samples characterized by moderate radiation levels and high greenery. In contrast, streets with high radiation exposure but insufficient greenery generally correspond to lower perceptual evaluations, while streets with low radiation but limited greenery do not exhibit clear perceptual advantages. This finding suggests that greenery mitigates solar radiation exposure and plays a critical moderating role in shaping perceptual experience at the street scale.

Single-dimension perceptual analysis indicates that solar radiation is significantly negatively correlated with positive perceptual indicators (Safe, Lively, Beautiful, Wealthy) and significantly positively correlated with negative perceptual indicators (Boring, Depressing) ($p < 0.001$). Meanwhile, greenery ratio is significantly positively associated with comprehensive perception scores, whereas sky view factor is significantly negatively associated with comprehensive perception, further confirming the importance of shading conditions and greening configuration in enhancing street experience quality (Figure 7).

4 Discussion

4.1 Urban Spatial Mechanisms

The findings reveal that in high-density subtropical cities, street-scale solar radiation is not uniformly distributed but is highly dependent on street morphological structure. Sky exposure and greenery coverage constitute two core spatial variables influencing radiation exposure. The coordinated configuration of different elements determines the stability of microscale light environments within streets.

Compared with previous studies that have discussed solar radiation primarily from the perspective of thermal comfort or energy balance, this research further identifies a non-linear relationship between solar exposure and subjective perception. Perceptual experience does not reach its optimum under the lowest radiation conditions, but rather within a moderate radiation interval. This phenomenon suggests that street experience may be jointly influenced by visual brightness, spatial openness and thermal exposure, rather than by a single physical intensity factor.

Furthermore, the role of greenery extends beyond reducing solar radiation intensity; it also enhances visual layering and psychological comfort within street space, thereby strengthening the adaptability of streets to environmental variation. This mechanism of “perceptual resilience” provides a new explanatory pathway for understanding the relationship between morphological structure and subjective experience.

4.2 Implications for Urban Design

The identified “moderate radiation-high perception” interval offers a quantitative reference for street-scale design. Rather than simply emphasizing shading or openness, the findings suggest that spatial form should achieve a dynamic balance between solar access and comfort regulation.

At the level of street cross-sections and spatial configuration, the results suggest that when sky view is maintained at approximately 30-45% and greenery coverage at approximately 35-50%, solar exposure remains relatively stable (PD $\approx$ 0.40-0.55) and corresponds to the highest composite perception scores. This range can be interpreted as a street-scale “perceptual comfort window,” providing quantitative guidance for street section design, vegetation arrangement, and spatial renewal. Excessively open spatial forms tend to result in excessive radiation exposure, while overly shaded environments may reduce spatial brightness and perceived safety; both conditions are detrimental to high-quality street experiences.

In terms of specific intervention strategies, streets characterized by high radiation exposure and insufficient greenery should prioritize the introduction of continuous tree canopies, structured shading facilities, and pedestrian buffer zones to reduce localized radiation intensity, rather than simply pursuing greater openness. Conversely, for streets with relatively low radiation but insufficient perception quality, moderate increases in spatial permeability, improved façade continuity, or adjustments to vegetation density can enhance daylight access and visual connectivity, thereby improving overall perception. Such radiation-threshold-oriented fine-grained regulation helps avoid one-size-fits-all design approaches.

At a broader scale, the results highlight the need to incorporate "solar radiation-perception balance" into the core indicator systems of urban renewal, walkability enhancement, and climate-adaptive planning. In areas with high solar exposure, solar energy utilization potential can be considered in tandem with pedestrian comfort to achieve synergy between energy efficiency and human experience. In contrast, in areas with dense greenery but insufficient daylight, refined management strategies are needed to achieve a dynamic balance between illumination and shading. The radiation threshold model proposed in this study provides a basis for parametric evaluation in urban design, establishing computable and comparable links among spatial configuration, microclimate regulation, and perceptual quality.

Overall, this study establishes an empirical framework linking urban morphology, solar microclimate and street perception, thereby providing quantitative evidence to support climate-adaptive urban design.

4.3 Limitations and Future Research Directions

Despite systematically revealing the spatial relationship between solar radiation and street perception using large-scale street view data, this study has several limitations that warrant further exploration. First, the street view imagery employed in this study is primarily concentrated in the high-radiation season from May to October and does not capture winter conditions characterized by lower solar angles or seasonal vegetation changes. This may limit the extrapolation of the results across the full annual cycle. Future research could integrate multi-season and multi-temporal street view imagery with measured radiation data to construct temporally continuous solar exposure models and improve spatiotemporal representativeness.

Second, street perception is influenced not only by solar radiation and spatial morphology but also by other microclimatic factors, such as cloud cover, air quality, atmospheric transparency, and surface albedo. These variables were not incorporated into the current analytical framework, which may lead to an underestimation of the combined effects of multiple climatic factors. Future studies could incorporate meteorological observations, air quality data, and more refined radiation simulation methods to further disentangle the relative contributions of different environmental elements to street perception.

Third, street perception indicators in this study were predicted using the MIT Place Pulse 2.0 dataset. While this dataset offers broad international coverage and strong cross-city generalizability, its crowdsourced nature and cultural-context differences may introduce potential biases. Recent studies have suggested that, in Chinese urban contexts, the dataset may overestimate certain negative perception dimensions (Rui & Cai 2025). It should be emphasized that the primary focus of this study is not the absolute level of perception scores, but rather

the relative differences, spatial distribution patterns, and nonlinear responses of street perception under varying levels of solar radiation. Within this analytical framework, the learned visual feature weights and spatial gradients remain highly informative. Nevertheless, future research should combine localized perception surveys or experimental evaluation methods to further calibrate and validate predictions based on international crowdsourced datasets, thereby enhancing the accuracy and credibility of perception modelling in specific cultural contexts.

Finally, this study focuses on Shenzhen's central urban area as a single case, and its conclusions require validation across cities with different climatic and morphological contexts. Future research could adopt a multi-city comparative approach, integrating remote sensing, socioeconomic, and land-use data to develop more generalizable modelling frameworks, thereby informing street design and climate adaptation strategies across diverse climate zones and urban forms.

5 Conclusion

This study systematically characterized the spatial distribution of street-scale solar radiation in Shenzhen's central urban area by integrating street view imagery, solar trajectory models, and prediction methods, and quantitatively analysed its relationship with street perception. The results demonstrate that street spatial morphology exerts a significant regulatory effect on solar exposure: increased sky view substantially enhances direct solar radiation, while building obstruction and street greenery effectively reduce solar exposure and are associated with more positive street perception.

Empirical analysis further reveals a stable negative correlation between solar radiation and composite perception scores, exhibiting a pronounced nonlinear pattern. Extremely high or low radiation environments are both unfavourable for positive subjective experience, whereas streets with moderate radiation levels are more likely to achieve higher composite perception ratings. These findings indicate that urban street lighting is not "the stronger or weaker, the better," but instead has an optimal range that favours perceptual experience. Street greenery plays a critical moderating role, not only by mitigating solar radiation but also by enhancing visual comfort and psychological perception, thereby strengthening spatial appeal.

Methodologically, this study combines large-scale street view data, geometric radiation estimation, and deep learning-based perception modelling to achieve high-resolution quantification of urban microscale solar exposure and subjective experience. This framework overcomes the spatial limitations of traditional meteorological observations and remote sensing data at the street scale, providing a generalizable technical approach for exploring the coupling between urban form, microclimate, and human perception.

Overall, the study empirically demonstrates that street-scale solar radiation is an important environmental factor influencing urban spatial perception, with its effects contingent on the joint configuration of spatial form and greenery. The findings provide quantitative guidance for balancing daylight utilization, street design, and pedestrian experience in subtropical high-density cities, and offer new evidence supporting the integration of perception-oriented evaluation into climate-adaptive urban design.

Nevertheless, studying has several limitations. The street view data primarily cover the high solar radiation period in summer and do not capture radiation variations throughout the year. In addition, the perception prediction model is based on an international crowdsourced dataset, which may introduce cultural bias in the Chinese urban context. Environmental factors such as cloud cover, atmospheric transparency, and surface materials were not incorporated into the analysis. Future research could incorporate multi-season and multi-city samples, combined with localized perception surveys, behavioural data, or experimental methods, to more rigorously and robustly validate the solar radiation-perception relationship, thereby enhancing the applicability of the findings across different cities and cultural contexts.

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Planning for Climate-Resilient Regions

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Abstract: Processes resulting from humans' interactions with nature have global, but territorially diverse impacts when they interact with locally specific natural and socio-economic features. To address associated challenges, societies need to design and implement sustainable responses that are territory-specific and socially feasible. This contribution presents a planning approach based on an IGC (International Geodesign Cooperation) framework and tools, which has been tested on several occasions in both academic settings and regional planning practice. The approach involves the interchange of scenario development and evaluation, utilising GIS support and a negotiation process. The adaptations of the original approach include the explicit use of evaluation in scenario development, the interchange of forecasting and back-casting for scenario development, and the partial aggregation of scenario elements into environment, society, and economy groups. The contribution presents and discusses the benefits of these adaptations for learning outcomes and addressing climate change adaptation.

Keywords: Climate change, landscape planning, evaluation, scenarios, geodesign

1 Introduction

Nations around the world face a growing challenge in planning, managing, and financing infrastructure essential to address major demographic shifts and weather events associated with a changing climate. In 2018, at the instigation of Carl Steinitz, Brian Orland, and Tom Fisher, ninety global university teams agreed to collaborate on creating scenario-driven designs for local-to-regional scale study areas to address future changes. The generic problem that the initiative aims to address is: How do we organise and conduct the initial and strategic stages of designing for longer-term change in a large, multi-system, multi-client, and contentious context, where our goal is concurrence and agreement? (STEINITZ & ORLAND 2021). Since its inception, approximately 150-member university teams from 50 countries have participated in the International Geodesign Collaboration, or IGC, each year.

IGC provides a common framework and conventions for content and methods, enabling the synthesis of contributions from different countries and contexts (STEINITZ & ORLAND 2021) and the analysis and assessment of outcomes (GU et al. 2020). These conventions include the scenario timelines (2035 and 2050) and the logic, which describes society's response to a set of identified driving forces. The "Non-Adopter" scenario explores the effects of the driving forces without adopting adaptation and mitigation measures; the "Early Adopter" scenario introduces a set of (climate) innovations (actions); and the "Late Adopter" does so only after 2035. The scenarios are evaluated against the UN's Sustainable Development Goals. The planning elements are "spatial systems" (land uses) and include water, green infrastructure, forests, agriculture, housing, institutions, industry, energy, and tourism. The process of developing the scenarios follows the "Framework for Geodesign", a sequence of steps and associated models (STEINITZ 2012). According to this sequence, the scenarios are developed in step 4 ("change models") and then evaluated in the following step ("impact models").

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Over the last decade, geodesign has gained momentum in academia as an approach that mediates the consideration of the environmental dimension of planning through collaboration and negotiation, relying on digital computational and communication technologies (CAMPAGNA 2023). The amount of projects produced in study processes as well as in practice allows reflections and evaluation, which confirms its value in terms of producing more sustainable and resilient planning projects (GU et al. 2020), as well as achieving a better understanding by all the involved actors about the complex territorial development challenges, and finding consensus on spatial development schemes (CAMPAGNA 2022). As an academic tool, the geodesign methodology is recognised as a reliable way to improve teaching objectives, with the geodesign framework interpreted in different ways (MOURA et al. 2023). The identified shortcomings of the approach include its failure to address process relationships, which may reduce the diversity and dynamics of design outcomes (CAMPAGNA 2023).

The IGC approach has been practised since its beginning in 2018-19 in the first-year studio of the master's program in landscape architecture at the University of Ljubljana. A variety of scales and territories have been addressed, ranging from the nationwide spatial development strategy to the regional scale (NUTS3) and the cross-border metropolitan area. The experience from the first couple of iterations showed that the task's complexity led to a number of required outputs (analyses, scenarios, evaluations) that students have difficulty producing and using coherently. The evaluations were done rather superficially and "on top" of the main design task, delivering scores that mainly reflect the "bad", "good", and "medium" quality of the scenarios, lacking substantial argumentation. Some of the ideas for "early adopter" scenarios were too idealistic and lacked the means to implement them.

The purpose of this paper is to present a framework for teaching geodesign using scenarios and evaluation, and suggest adaptations of the IGC approach developed through several iterations in the studio (Figure 1).

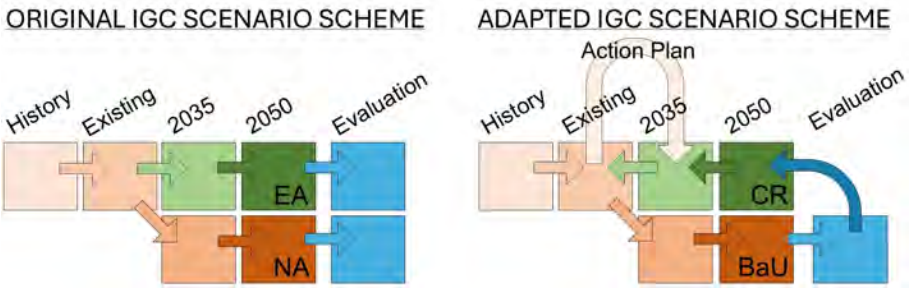

Fig. 1: The original – left (ORLAND, 2019) and our adapted IGC scenario scheme (right). EA – early adopter scenario, NA – non adopter scenario, CR – climate resilient scenario, BaU – Business as usual scenario.

These adaptations are illustrated through case studies of the adapted IGC approach applied to a set of studio tasks addressing the regional planning scale and various aspects of climate change resilience. In line with EU and national policies, climate resilience is understood from both perspectives: reducing greenhouse gas emissions and adapting planned development to the expected impacts of climate change (JASPERS 2023). Climate challenges in Slovenian regions include sea-level rise, river floods, forest fires, heat waves, and droughts. Improving

regional climate resilience aligns with ongoing policy document preparation, such as regional spatial plans for all 12 regions in Slovenia, coordinated by the Ministry for Spatial Planning, and the development of the National Strategy for Climate Change Adaptation, coordinated by the Ministry for the Environment.

2 Materials and Methods

In line with the purpose of this paper, the description of methods focuses on the sequence of steps and their pedagogical intentions rather than on a detailed description of the data and specific modelling techniques. These vary considerably from year to year, depending on the area of study and the topic. These are well accepted and widely known in the planning community (e. g., multicriteria suitability modelling, overlay analysis, viewshed analysis, least-cost corridors). We use publicly available data from national government bodies, supplemented by OpenStreetMap and other sources.

According to the Geodesign framework, the entire planning process is repeated several times. In the studio, the first run (scoping) is conducted as an analogous brainstorming session, which gives students an idea of what they are dealing with and what the final product will entail. The second run (method definition) is conducted by the IGC team and teachers beforehand. Most of the time in the studio is devoted to the third run, in which the plan is produced by following a sequence of steps and adjacent "models" (STEINITZ 2012).

The first two steps (presentation and process models) consist of an area description based on available historical and current data on area features and processes. Evaluation models are developed as a SWOT analysis of the area, based on existing evaluations and references to policy documents.

Scenarios are used in the third step (change models), which is the most extensive part of the studio. Although each year different issues come to the forefront, the scenarios address spatial development comprehensively, considering all land uses ("spatial systems") in the area: 1) agriculture and forestry, 2) water infrastructure, 3) green infrastructure, 4) transport infrastructure, 5) energy infrastructure, 6) industry and commerce, 7) residential areas, 8) institutions, 9) tourism. The elements of the scenario are chosen based on the area characteristics and the scale of planning (from 1:50.000 to 1:250.000). Each group of students conducts a set of analyses to provide an inventory, identify driving forces for change, and assess the spatial suitability of their land use.

The scenario timelines are the same as in the original IGC approach (2035 and 2050), and logic assumes different responses to a set of identified driving forces. We use only two scenario logics: the "Business as usual" (BaU) scenario, which explores the effects of driving forces on spatial potentials and natural resources, and the "Climate response" (CR) scenario, which sets targets and presents design solutions.

The "Business as usual" (BaU) scenario starts by developing scenarios for each land-use system, which are then synthesised into a common scenario. To develop this scenario, students explore the dynamics of each land use in the past and extrapolate those dynamics into the future, taking into account current planning and implementation documents. This scenario is first prepared for 2035, and then for 2050.

The fourth step is the impact model. The impacts of Bau scenario are evaluated in three levels of reference: (1) the 17 UN Sustainable Development Goals, (2) the goals from the National Spatial Development Strategy (Spatial planning document adopted by the parliament, providing spatial concept and setting priorities and goals for spatial development of the whole country), and (3) the internal coherence between the systems (as outlined in the interaction matrix in which the synergies and conflicts between systems are identified). Each group evaluates how their land use system in the BaU scenario contributes (or not) to SDGs and Spatial Development Goals. They also evaluate how other systems' proposal affects their system. This assessment is primarily qualitative, but it is supported by overlaying areas of proposals with evaluations of the territory (e. g. suitability maps for each land use system, habitat maps, water reservoirs, agricultural land quality, other students' proposals, etc.), as well as literature on the past impacts of similar land-use changes. The students assign the scores using a 5-point scale from -2 (large negative impact) to +2 (large positive impact) and provide arguments. Each student needs to adapt the evaluation tools to their land-use system and the relevant reference documents. A presentation is done at this point to calibrate and discuss the scores. The Results section provides a summary of scores from the past three studios to show general trends and patterns.

Based on evaluations of the 2050 BaU scenario, the "Climate Response" (CR) scenario is first prepared for 2050. Not all aspects of the BaU scenario are negative, and these require no specific action. On the other hand, the changes that cause conflicts or diverge from national and global objectives do need to be addressed. After each team prepares a CR scenario for their own system, the systems are grouped into three categories: "environmental" (including green infrastructure, forests, agriculture, and water), "social" (housing and institutions), and "economy" (transport, energy, and industry). Each group develops a comprehensive scenario tailored to its objectives. Then, negotiations among groups are conducted to resolve conflicts in a win-win manner or to find a better solution. The society and the economy groups are usually more compatible, so they negotiate first to propose a common scenario. Afterwards, this scenario is negotiated with the environmental group to finalise the plan. This process not only removes conflicting proposals but also produces alternative, possibly beneficial solutions.

The resulting CR scenario is then evaluated to determine if and how it has improved compared to the BaU scenario. The CR scenario is then backcast to 2035. The students have to decide which elements of their (land-use) scenario are feasible and/or necessary to implement first. Then they present their proposals and verify if their scenario fits with those of the other spatial systems. The last step is preparing the action plan, in which each group proposes the implementation instruments that will enable them to achieve the planned changes by 2035.

The studio's educational impact is evaluated each year through an anonymous survey in which students reflect on the course. We use the findings from this survey to show the self-recognised benefits of the presented approach for the education of landscape architects.

Another check is observing the same students' work process in the design studio the following semester, and receiving peer feedback from colleagues teaching the design studio.

3 Results

In this chapter, we summarise the experience from three studios developing the "Business as usual" (BaU) and "Climate response" (CR) scenarios for the southwestern regions of Slovenia, namely Primorsko notranjska (Figure 2), Goriška and Obalno Kraška regions.

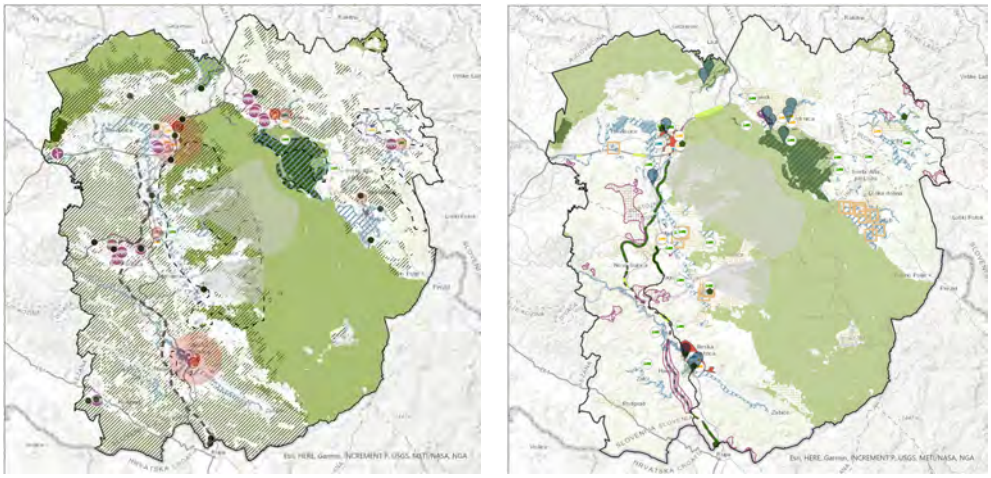

Fig. 2: Example of Business as Usual (left) and Climate Response scenario (right) for Primorsko Notranjska region

Each scenario addresses the uncertain consequences of climate change in a different way. The BaU scenarios react late, when climate impacts are already severe, and mostly in a technical way. Proposals in CR scenarios are more diverse, but they can be grouped into the following strategies:

- Optimising land-use to avoid the (present and future) most vulnerable (landslide, flood and fire-prone) areas, including pre-emptive measures such as removal of vulnerable infrastructure and housing from areas likely to be severely impacted in the future;
- Using nature-based and multifunctional solutions to mitigate the climate change impacts (extensive agriculture and introducing wetlands to enable flooding and retain water instead of concrete flood protection and river regulation; introducing new green spaces to mitigate heat waves in urban areas, designing fire clearances as recreation paths);
- Designating areas for renewable energy production (wind, solar, hydrogen) and improving low-carbon mobility (improving public transport, park and ride systems, EV-charging stations).

The comparison of BaU and CR scenarios in terms of inter-system impacts shows that the overall cohesion increased in the CR scenario. Most conflicts were resolved, and some additional synergies were gained. The impacts of industry on other systems improved most, followed by settlements. Water and agriculture systems in CR profited the most from the impacts of other systems. Nevertheless, some specific conflicts increased, such as the negative

impacts of agriculture on settlement due to stronger protection of agricultural land in the CR scenario. An aggregated summary of the cohesion results from three studio projects shows that CR scenarios achieve greater synergies among sectors within groups (economy, society, and especially environment) and reduce conflicts between economic, society, and environmental sectors in all combinations (Figure 3).

Business as usual scenario

IMPACT SOURCE	IMPACT RECIPIENT: Society	Econo.	Environ.
Society	32	29	-9
Econo.	25	27	11
Environ.	-4	-1	66

Climate response scenario

IMPACT SOURCE	IMPACT RECIPIENT: Society	Econo.	Environ.
Society	20	20	-34
Econo.	13	18	-25
Environ.	-10	-2	22

Fig. 3: Aggregated summary of the cohesion results from three studio projects. CR scenarios (left) as compared to BaU (right).

On the global scale, most of the SDGs were found to be affected by at least one or two systems. Least relevant is the “gender equality”; most impacted are the “decent work and economic growth”, “industry and infrastructure” (in BaU scenarios) and “sustainable cities and communities”, “good health and wellbeing” and “decent work and economic growth” (in CR scenarios). The improvement from BaU to CR scenario (Figure 4) is most significant in the case of SDGs “climate action” – as expected, but also “sustainable cities and communities” and “good health and well-being”. In reference to the national-scale objectives, the scenarios differ most in their contribution to the goal of “resilience and adaptability”, where CR performs noticeably better. Settlement and agriculture are two systems that improve mostly from the BAU to CR scenario, each in reference to a different set of goals, but both within the “climate action” domain.

In terms of teaching outcomes, the surveys of students’ satisfaction with the course show that they find this learning experience useful and important for their planning competences. When they are asked to reflect on the studio, some typical answers are (students in studio 24-25): “The project highlighted the need for a holistic approach that involves collaboration between different stakeholders and the coordination of different goals to achieve sustainable development by 2050.” They also perceive the skills to be helpful in their professional development: “It was interesting to see how I started to apply the knowledge I gained from this project to other assignments and to other subjects.” And: “Cooperation between the groups was also an important part of the process, which brought better results. Learning about scenarios as a tool for managing possible events and other knowledge that we have gained in the course seems to me to be of key importance in further practice.”

Observation of students' work in the next semester shows differences in cases where the design projects are located in the areas previously covered in the planning studio. The students tend to approach their design task differently, testing various scenarios and evaluating their designs against a broader set of objectives.

Difference of SDG evaluations between Climate Resilient and Business as Usual scenario

SUSTAINABLE DEVELOPMENT GOAL	RES	INST	TRN	TUR	IND	ENE	AGR	FOR	WAT	GRN	SUM
1: No poverty	0	2	1	3	-1	3	6	-1	2	0	**15**
2: Zero hunger	3	0	1	2	3	0	6	-1	4	-1	**17**
3: Good health	5	10	9	7	5	3	5	7	8	4	**63**
4: Quality education	2	8	1	-1	2	1	-1	0	0	2	**14**
5: Gender equality	1	1	0	0	0	0	0	0	0	0	**2**
6: Clean water, sanit.	11	1	5	5	8	2	3	1	7	6	**49**
7: Affordable, clean en.	8	0	0	5	7	4	1	2	0	-1	**26**
8: Dec. work, ec. grow.	6	5	3	11	4	6	7	1	4	0	**47**
9: Ind., inn. and infr.	5	1	4	3	4	4	3	3	3	-1	**29**
10: Reduced inequalities	7	5	0	1	1	0	0	0	2	0	**16**
11: Sust. cities, comm.	17	5	14	4	10	7	7	2	10	8	**84**
12: Resp. cons., prod.	5	0	-2	6	7	2	10	3	5	0	**36**
13: Climate action	11	1	13	2	14	7	11	5	11	10	**85**
14: Life below water	1	2	2	4	6	1	8	0	7	6	**37**
15: Life on land	5	2	7	-1	9	0	12	0	8	11	**53**
16: Peace, just., str. inst.	1	4	2	0	-1	0	0	0	0	0	**6**
17: Partn. for the goals	3	4	-1	3	0	1	3	2	3	2	**20**
SUM	**91**	**51**	**59**	**54**	**78**	**41**	**81**	**24**	**74**	**46**	**599**

Fig. 4: Aggregated summary of each land-use system's contribution to Sustainable Development Goals (RES – residential, INST – institutions, TRN – transport, TUR – tourism, IND – industry, ENE – energy infrastructure, AGR – agriculture, FOR – forestry, WAT – water, GRN – green infrastructure)

4 Discussion

Geodesign (and IGC) have been around for some time, and the recent global challenges only prove the relevance of its global perspective and comparable approach. By studying and interpreting global change assumptions, the students learn to consider the potential spatial consequences and future needs of their area. This helps them define the content of their plans and set the objectives. The experience led us to introduce changes to the original approach, which improved learning outcomes and resulted in more coherent, better final plans.

The key innovations in our IGC approach, compared to the original idea, concern how the scenarios and evaluations are used and positioned within the project development. The BaU is an exploratory / forecasting scenario, while the CR is a normative / back-casting scenario. As such, they are not directly comparable, and the methods for developing and using them

differ, which influences the studio's design in two main ways: first, the BaU scenario is evaluated before developing the CR scenario, and the results explicitly inform the CR scenario. Secondly, the CR scenario is developed first for 2050 and then backcast to 2035 and 2025 as an action plan (see Figure 1). Using them interchangeably (scenario – evaluation – new scenario – evaluation) helps to optimise the proposals. The evaluation is therefore explicitly used as a design tool, at two levels: disaggregated and aggregated. Evaluation of each system in terms of its performance in reference to (global and national) objectives of (sustainable) development and the internal coherence of the scenario provides concrete information for improvement, addressing single land use systems and relevant goals, or a pair of land use systems. The strategic level of evaluation is achieved by aggregating the evaluation elements across the society, environment, and economy groups (RADEJ & GOLOBIC 2021). While this entails certain generalisations, it helps to identify general (un)sustainable characteristics of scenarios and enables formulating the strategy of the (regional) spatial development.

While evaluations as a design tool are the IGC approach's most significant contribution, they remain mostly qualitative and argumentative. Many of the SDGs could be assessed using quantitative models, but developing those models exceeds the scope of this studio. Developing such models with sufficient flexibility to adapt to regional specifics could be a future task for the IGC community. One example is the development of a CO2 calculator based on average emissions for a specific land use.

Another innovation is using the back-casting for CR scenario from 2050 to 2035 and then to the present. This enables identification of priorities and actions for timely implementation. It also grounds the proposals in the 2050 CR scenario through existing and actionable measures, making them more tangible and convincing when presenting the results to stakeholders.

All these competences are not only relevant as academic outputs but can also be trained in planning practice through “geodesign workshops” that usually take one or two days. The first three models are thus prepared by a team of geodesign experts and used as the knowledge base for a workshop with stakeholders, in which alternative scenarios are produced, evaluated, and, through collaboration and negotiation, lead to consensus with regard to a final agreed scenario« (CAMPAGNA 2023). Such workshops were conducted early in the development process of regional spatial plans for two Slovenian regions (PIPAN et al. 2023). It proved to be a fruitful and engaging experience, providing a solid basis for the actual planning process and a better understanding among stakeholders of their concerns and aspirations.

Based on our experience with IC in teaching and practising spatial planning, we agree with M. Campagna's [2023] observation that the geodesign framework is an effective reference for teaching (and practising) planning in complex situations. It is robust enough to accommodate modifications as required across different contexts, while still providing clear and comprehensive guidance for both teachers and students.

Acknowledgments

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A Digital Morphology-Ecology Response Model for the Optimization of Urban Blue-Green Spaces in High-Density Cities

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Abstract: High-density urban development has led to increasing fragmentation of blue-green spaces, which constrains the realization of ecological benefits. This study applies machine learning and SHAP analysis to identify the relationships between morphological characteristics of blue-green spaces and ecological benefits, and constructs a morphology-ecology response model to support ecological benefit prediction and morphological optimization within urban planning schemes. The iterative nature of the model makes it applicable to most urban blue-green space planning scenarios. It enables future planning regulation under the condition of coordinated optimization of morphology and ecology, thereby supporting the scientific planning of urban blue-green spaces.

Keywords: Blue-green spaces, morphological characteristics, ecological benefits, random forest, optimization methods

1 Introduction

There is a close relationship between the morphological characteristics of urban blue-green spaces and their ecological benefits (SHOU et al. 2025). In high-density cities, blue-green spaces are increasingly encroached upon and fragmented, with their morphology becoming more regular and fragmented (PAULEIT et al. 2005), which limits the realization of ecological benefits. The relationship between morphology and ecological performance is coupled and interdependent. Predicting ecological benefits based on morphological characteristics (CAI et al. 2023), or optimizing morphology based on ecological objectives (SHENG et al. 2024), has become an important research focus. With the development of artificial intelligence, machine learning methods represented by random forest can support complex association analyses under multi-objective and multi-scenario conditions, helping to reveal the mechanisms driving urban spatial change and to predict future spatial development (KHEIR et al. 2008). Based on the use of a random forest model to analyze the relationships between morphological characteristics and ecological benefits of urban blue-green spaces, this study constructs an ecology-morphology response model to enable ecological benefit prediction and blue-green space morphological optimization.

2 Study Area and Data

Nanjing (31°14′-32°37′N, 118°22′-119°14′E) is a megacity in China where urban blue-green spaces have experienced substantial disturbance and a high degree of fragmentation during the process of urban development. The datasets used in this study include multispectral remote sensing imagery, DEM data, urban land-cover data, urban soil type data, and meteoro-

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logical data for Nanjing. According to the international land-use classification system (Land-Use and Land-Cover Change, LUCC), land use in Nanjing's central urban area in 2020 was classified, with forests, grasslands, and croplands categorized as urban green spaces, water bodies classified as urban blue spaces, and construction land and unused land designated as gray spaces (Figure 1).

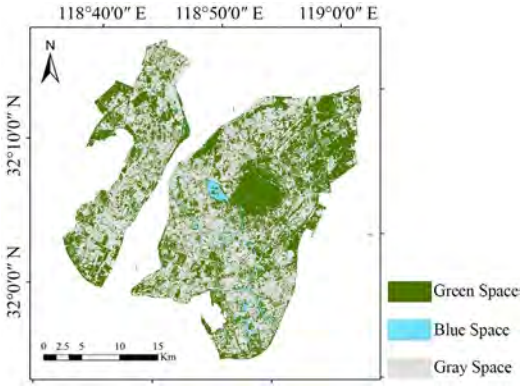

Fig. 1: Distribution of urban blue-green spaces in Nanjing's central urban area in 2020

3 Methodology

The construction of the blue-green space "morphology-ecology" response model consists of four stages, as illustrated in Figure 2: (1) development of indicator sets for morphological characteristics and ecological benefits; (2) model fitting based on the random forest algorithm; (3) model interpretation using SHAP; (4) iterative optimization based on the response model.

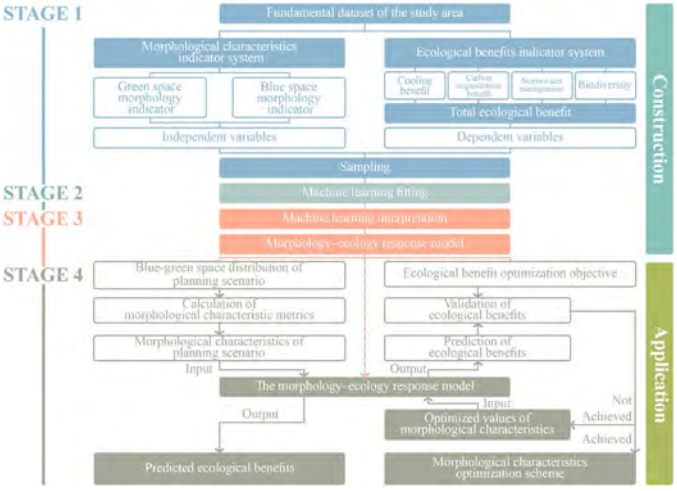

Fig. 2: Research framework of this study

Second, model fitting was conducted based on the random forest algorithm. Eighty percent of the dataset was used as the training set to establish the response relationship between morphology and ecology, while the remaining 20% served as the testing set to evaluate fitting accuracy and model performance. When constructing each decision tree, two-thirds of the training data are randomly sampled for fitting, leaving one-third as out-of-bag (OOB) data. The random forest model evaluates the importance of each variable by comparing the OOB fitting error before and after the variable is permuted. In random forest modeling, the number of decision trees (numTrees) is the primary parameter influencing model accuracy and computational performance. In this study, the coefficient of determination (R^2), mean absolute error (MAE), and model runtime (T) were used as evaluation criteria, with R^2 greater than 0.7 defined as the necessary condition for model accuracy validation to select an appropriate number of decision trees. Cross-validation was performed during each training-testing split, and the mean value of multiple validation results was adopted as the final indicator for model accuracy assessment.

Third, the response model was interpreted using SHAP (SHapley Additive exPlanations. As the response model constructed by the random forest algorithm essentially functions as a "black box," the SHAP interpretation method (LUNDBERG et al. 2017) was employed to quantify the influence of individual morphological characteristic indicators on ecological benefits, thereby elucidating the underlying mechanisms linking blue-green space morphology and ecological performance.

Finally, the response model was applied for iterative optimization and validation. The model enables the prediction of ecological benefits based on morphological characteristics and supports iterative optimization of blue-green space morphology according to predefined ecological benefit objectives, thereby deriving target values for urban blue-green space morphological characteristics. Prior to executing morphological optimization iterations, preliminary response model analyses were used to determine the general direction of morphological indicator adjustment and to establish corresponding adjustment rules. During the optimization process, the maximum number of iterations for morphological indicator adjustment was set to 5000. When improved ecological benefits were achieved, the corresponding morphological characteristic sequences were output. The Landscape Generator (LG) platform (SLAGER et al. 2013) was employed to convert between morphological characteristic sequences and spatial morphological patterns. The resulting optimized schemes were then reintroduced into the morphology-ecology response model to verify whether the expected ecological benefit optimization outcomes had been achieved.

4 Results and Discussion

4.1 Mechanisms Linking Morphological Characteristics and Ecological Benefits

Based on the results of correlation and importance analyses of morphological indicators, indicators with importance values lower than 0.3, as well as those with correlation coefficients exceeding 0.8 and relatively low importance, were excluded. The key indicators retained for model construction were VCA_{Blue}, $VLPI_{Green}$, AI_{Green}, LSI_{Green}, and $COHESION_{Blue}$. The calculated results for land surface temperature (LST), net primary productivity (NPP), carbon

storage (C_{total}), surface runoff (Q), waterlogging point density (F_n), and habitat quality (HQ) in Nanjing in 2020 are shown in Figure 3(a)–(f), while the overall ecological benefits （ECO） are presented in Figure 3(g).

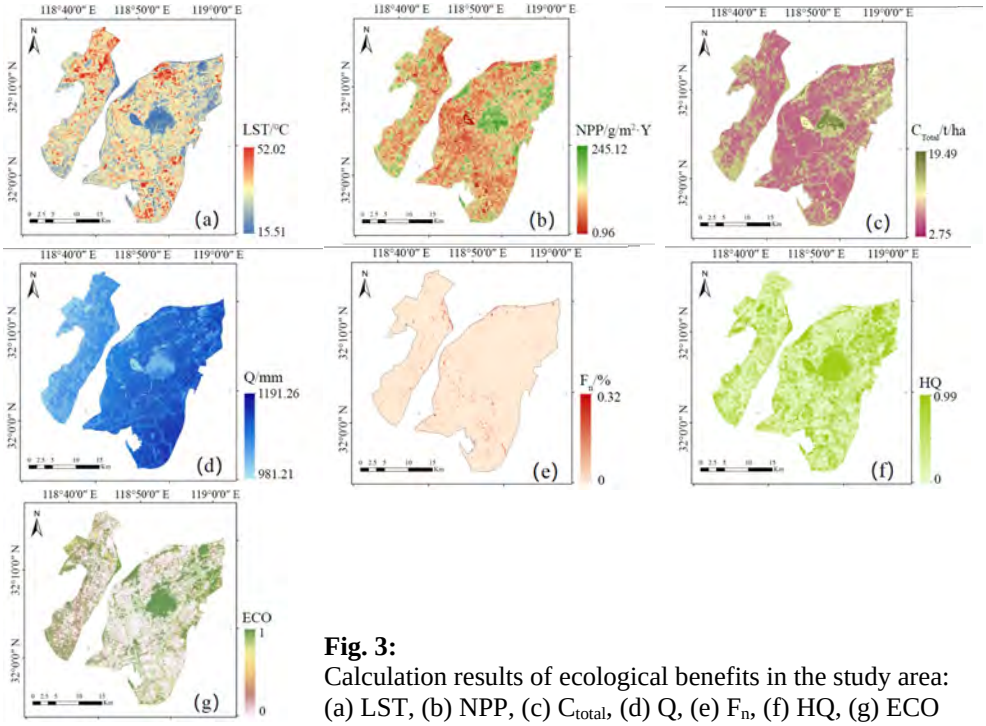

Fig. 3:
Calculation results of ecological benefits in the study area: (a) LST, (b) NPP, (c) C_{total}, (d) Q, (e) F_n, (f) HQ, (g) ECO

In this study, the optimal number of decision trees was determined to be 100, with MaxNumSplits set to 10, MinLeafSize set to 8, and the random number generator (rng) value set to 43. After running the random forest algorithm, both the training and testing datasets achieved R^2 values greater than 0.7 and MAE values lower than 0.1, indicating that the constructed response model is capable of accurately predicting ecological benefits based on morphological characteristics. From a global perspective, $VLPI_{Green}$ exerted the greatest influence on the model output, exhibiting both positive and negative effects. VCA_{Blue} and AI_{Green} had the next strongest influences and were predominantly associated with positive effects. LSI_{Green} and $COHESION_{Blue}$ showed relatively smaller impacts on the model output, with LSI_{Green} tending toward negative effects and $COHESION_{Blue}$ toward positive effects. Local indicator dependency analysis of the response model facilitates the interpretation of specific regulatory values and directions for urban blue-green space morphological characteristics. Figure 4 illustrates the influence of individual morphological indicators on model outputs, as well as the effects of indicator values on predicted outcomes.

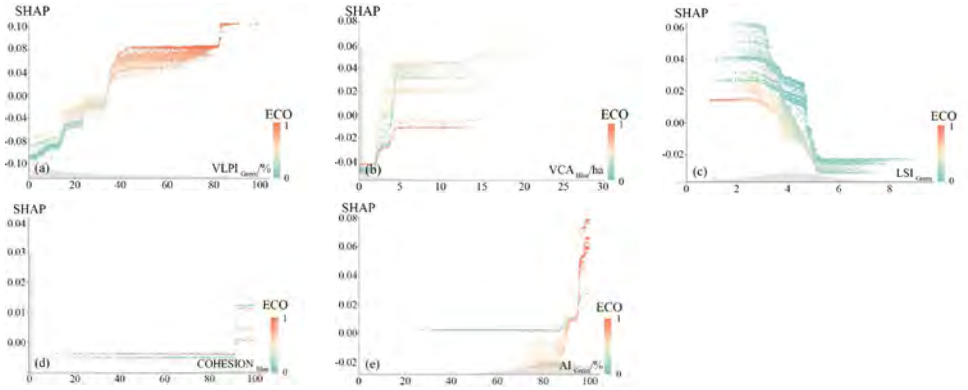

Fig. 4: Morphological characteristics index dependency analysis diagram: (a) VLPI $_{Green}$, (b) VCA $_{Blue}$, (c) LSI $_{Green}$, (d) COHESION $_{Blue}$, (e) AI $_{Green}$

4.2 Morphological Optimization Driven by Ecological Benefits

This study refers to the *Nanjing Territorial Spatial Master Plan (2021-2035)* and extracts the master plan of the central urban area of Nanjing as the baseline dataset. The response model is applied to predict ecological benefits and optimize morphological characteristics. The predicted ecological benefits are shown in Figure 5(a). The natural breaks method is used to classify the calculated ecological benefits of the planned scheme into five categories: excellent, relatively high, good, moderate, and poor. Based on the evaluation results, the optimization target is defined as areas where regions with poor ecological benefits account for more than 90%, as well as poor-benefit areas within urban blue-green spaces. Three typical areas are selected for subsequent morphological optimization, as shown in Figure 5(b). The areas to be optimized are not constrained by size or shape. To comprehensively consider surrounding conditions, a 500 m buffer zone is set after defining the selected boundary. The response model enables iterative morphological optimization and generates multiple schemes that meet the ecological benefit targets. Before outputting the final optimized sequence of morphological characteristics, a preliminary selection is conducted: schemes with higher ecological benefits are retained, and those closer to the original morphological characteristics are preferred. Accordingly, three optimized schemes are selected for each typical zone, achieving improved ecological benefits while minimizing morphological adjustments to blue-green spaces, thereby enhancing optimization efficiency.

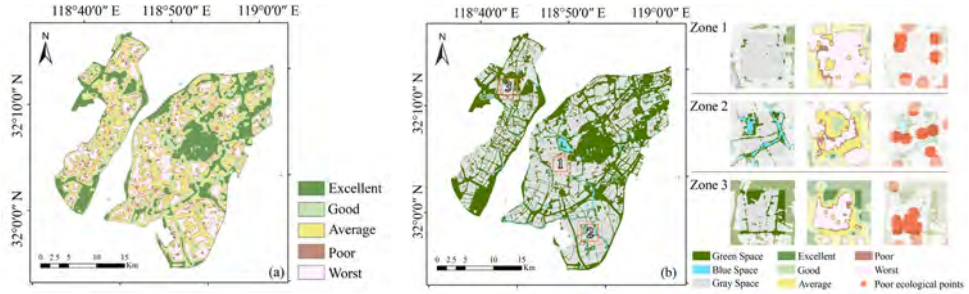

Fig. 5: Map of Nanjing's central urban area in 2035: (a) ecological benefits of Nanjing's central urban area in 2035, (b) typical optimized zones of blue-green spaces

4.3 Analysis of Optimization Schemes for Typical Zones

In Typical Zone 1, the optimization focuses on morphological adjustment under conditions where the area and proportion of urban blue-green spaces are relatively small. The strategy mainly increases the aggregation of green spaces and enhances the expansion of blue spaces (Figure 6(a)). Scheme 1 significantly increases AI_{Green} and achieves the largest improvement in ecological benefits, reaching 0.54. Scheme 2 markedly improves $COHESION_{Blue}$, resulting in ecological benefit enhancement in more than 49% of the area. Scheme 3 increases AI_{Green} while optimizing the edge configuration of green spaces. It performs best in overall improvement, with more than 52% of the area showing enhanced ecological benefits, and it achieves the highest mean increase, reaching 0.19.

In Typical Zone 2, morphological optimization is conducted without substantial changes in the overall area proportion of blue-green spaces. Instead, minor adjustments are made to their morphological indices, particularly at the interface between blue and green spaces, to enhance ecological benefits (Figure 6(b)). Scheme 1 increases $COHESION_{Blue}$ and enlarges LPI_{Green} around blue spaces, with almost no decline in ecological benefits after optimization. Scheme 2 introduces small green patches within gray spaces to increase AI_{Green}, while reducing LSI_{Green} around existing blue spaces. This scheme shows the most evident improvement, with approximately 57% of the area experiencing enhanced ecological benefits. Scheme 3 reduces LSI_{Green} and increases $COHESION_{Blue}$ at the blue-green interface, achieving the largest numerical increase in ecological benefits, reaching 0.39.

In Typical Zone 3, no blue spaces exist in the original planning scheme. Following the principle of minimal morphological change, the selected optimization sequences adjust only the area proportion, aggregation, and morphological indices of urban green spaces (Figure 6(c)). Scheme 1 significantly reduces LSI_{Green}; compared with Schemes 2 and 3, it results in a smaller proportion of improvement, with about 50% of the area showing enhanced ecological benefits. Scheme 2 increases AI_{Green} and raises $VLPI_{Green}$ in areas originally below 36% to nearly 36%. The maximum improvement reaches 0.31, and more than 50% of the area experiences enhancement. Scheme 3 markedly increases AI_{Green}, achieving the greatest overall improvement. The proportion of improved areas reaches 75%, while the proportion of areas with decreased ecological benefits is only 0.23%, and the maximum increase reaches 0.41.

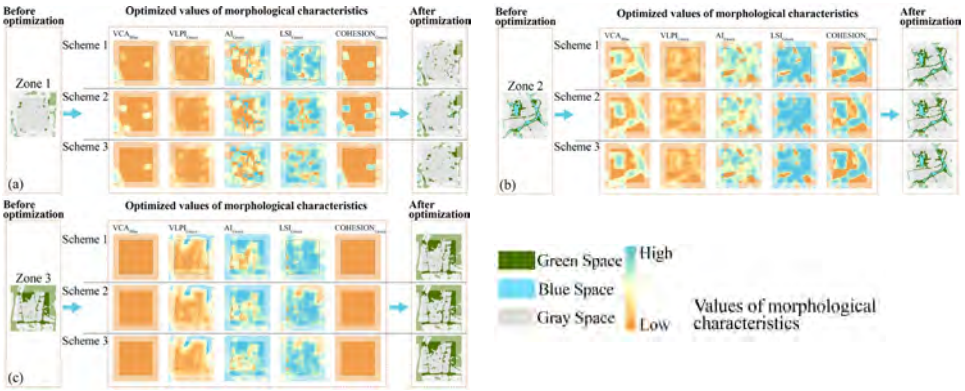

Fig. 6: Optimization scheme diagram of typical optimization areas in blue-green space: (a) Zone 1, (b) Zone 2, (c) Zone 3

5 Conclusion and Outlook

By constructing a morphology-ecology response model for urban blue-green spaces, this study systematically investigated the interactive mechanisms between morphological characteristics and ecological benefits. The proposed model provides quantitative support for future urban planning regulation under the premise of achieving synchronous optimization of morphological structure and ecological performance, thereby facilitating the scientific planning of urban blue-green spaces. The main conclusions are summarized as follows:

1) Areas characterized by high integration of blue and green spaces and strong water-green interweaving exhibit particularly prominent ecological benefits. In areas with relatively high ecological performance, optimizing blue space morphology alone is insufficient to further enhance ecological benefits; instead, coordinated interactions with green space morphological characteristics are required.

2) $VLPI_{Green}$ exerted the strongest influence on the response model outputs, exhibiting both positive and negative effects. VCA_{Blue} and AI_{Green} followed in importance and were predominantly associated with positive effects. LSI_{Green} and $COHESION_{Blue}$ had relatively weaker influences on model outputs, with LSI_{Green} mainly showing negative effects and $COHESION_{Blue}$ demonstrating positive effects.

3) When the area and proportion of urban blue-green spaces are relatively small, morphological optimization can be achieved by increasing AI_{Green} and $COHESION_{Blue}$. When the area proportion of blue-green spaces changes only slightly, synchronous fine-tuning of LPI_{Green} and $COHESION_{Blue}$ is recommended. In planning schemes lacking blue spaces, ecological benefit optimization should be realized through the regulation of $VLPI_{Green}$, AI_{Green}, and LSI_{Green}.

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Environmental Monitoring, Remote Sensing and Data Collection

Mapping Recovery: Digital Narratives of Bushfire-Affected Roadside Landscapes in New South Wales

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Abstract: Bushfire recovery is commonly assessed through ecological surveys, remote sensing, or infrastructure metrics, yet these approaches often overlook how recovery is perceived and experienced along everyday mobility corridors. This paper presents a digital landscape architecture methodology that uses Google Street View imagery, machine-assisted vegetation analysis, and narrative-based visualisation to analyse post-bushfire recovery in roadside environments. Focusing on bushfire-affected roads in New South Wales after the 2019–2020 fires, and using Bells Line of Road as a detailed case study, the study integrates species detection, vegetation percentage, sky openness, and vegetation community mapping to document structural and perceptual change over time. Results show increased visible species richness despite canopy loss, driven by greater sky openness and understorey exposure. Interpreted as narrative moments in landscape recovery, these findings position digital indicators as tools through which landscape architects can translate ecological change into design-relevant knowledge.

Keywords: Digital landscape architecture, bushfire recovery, google street view, roadside landscapes, sky openness, vegetation narratives

1 Introduction

The 2019-2020 bushfires in New South Wales (NSW), Australia, burned over five million hectares (NSW RURAL FIRE SERVICE 2020) and profoundly altered landscapes across regional ecological and road networks. For many communities, roads are the primary interface through which post-fire landscapes are encountered, remembered, and assessed. Despite this, post-bushfire recovery assessments are predominantly conducted through satellite imagery, ecological field surveys, or infrastructure audits, often detached from the perceptual scale at which landscapes are experienced (FRICKER et al. 2024). This paper posits that post-bushfire analysis can benefit from a complementary analytical lens focusing on roadside environments – one integrating ecological change with visual, experiential, and narrative dimensions.

Recent work in digital landscape architecture emphasises the role of landscape as an active medium through which climate change becomes perceptible and actionable, rather than as a passive surface to be quantified (STREMKE et al. 2023). Digital technologies, particularly street-level imagery such as Google Street View (GSV), offer opportunities to explore this gap by capturing landscapes from a human-eye-level perspective (LI et al. 2022, CHEN & DONG 2025). Unlike remote sensing, whose plan view does not correlate with human experience (BENEDIKT 1979), GSV captures landscapes from a human-eye-level perspective. GSV also enables longitudinal observation across multiple years through historic image archives. When combined with computational analysis, such imagery can reveal how ecological succession unfolds as a sequence of visible transformations along linear corridors (MELSOM & HURKXKENS 2023, BURMEISTER et al. 2023).

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This research asks: How can digital technologies reveal new ecological and perceptual dimensions of bushfire-affected roadside landscapes to enable interpretation informing landscape architecture practice?

2 Methodology

2.1 Site Selection and Data Collection

Fig. 1: Bushfire-affected road segments in New South Wales following the 2019–2020 bushfires. Bells Line of Road is highlighted as the case study. Basemap: Google Satellite imagery.

An initial GIS overlay of the 2019–2020 NSW bushfire severity map (NSW RURAL FIRE SERVICE 2020) and the state road network (TRANSPORT FOR NSW 2023) identified 40 bushfire-affected roads (Figure 1).

Bells Line of Road was selected for detailed analysis due to its significant exposure to bushfire, its ecological diversity-bisecting the Greater Blue Mountains Area World Heritage Area (UNESCO)-its visual prominence and historical significance, and the availability of long-term historical imagery through Google Street View. GSV imagery was extracted at 100-metre intervals along the road (Figure 2). Observation points were assigned at 100-metre intervals along the road centreline; however, only locations where multi-temporal Google Street View (GSV) imagery was available across all three temporal conditions were retained for analysis. As a result, the final set of 56 spatially fixed observation points was partially determined by the availability and continuity of historic GSV coverage. This constraint reflects a methodological limitation inherent in street-level archival datasets and is acknowledged as influencing spatial sampling density.

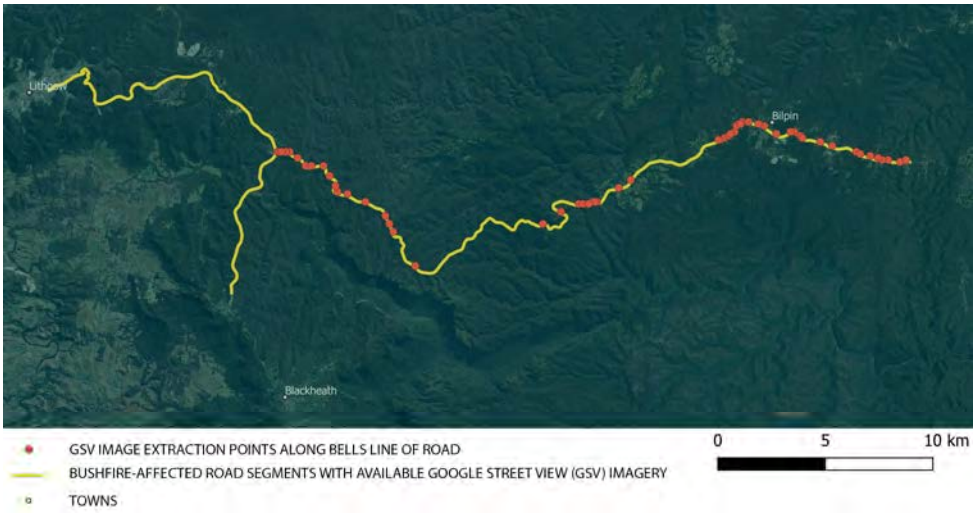

Fig. 2: Analysed observation points along Bells Line of Road, sampled at approximately 100 m intervals where multi-temporal Google Street View data were available

Three temporal datasets were compiled based on the closest available imagery to key fire milestones. Pre-fire imagery dated between 2015 and November 2019 (prior to the main fire front impact in December 2019). Fire-year imagery was drawn from images captured between January 2020 and December 2020, representing immediate post-disturbance conditions. Current recovery imagery dated between 2023 and early 2025, depending on availability at each observation point. Exact image capture dates were recorded for each point to ensure temporal comparability.

2.2 Species Recognition and Validation

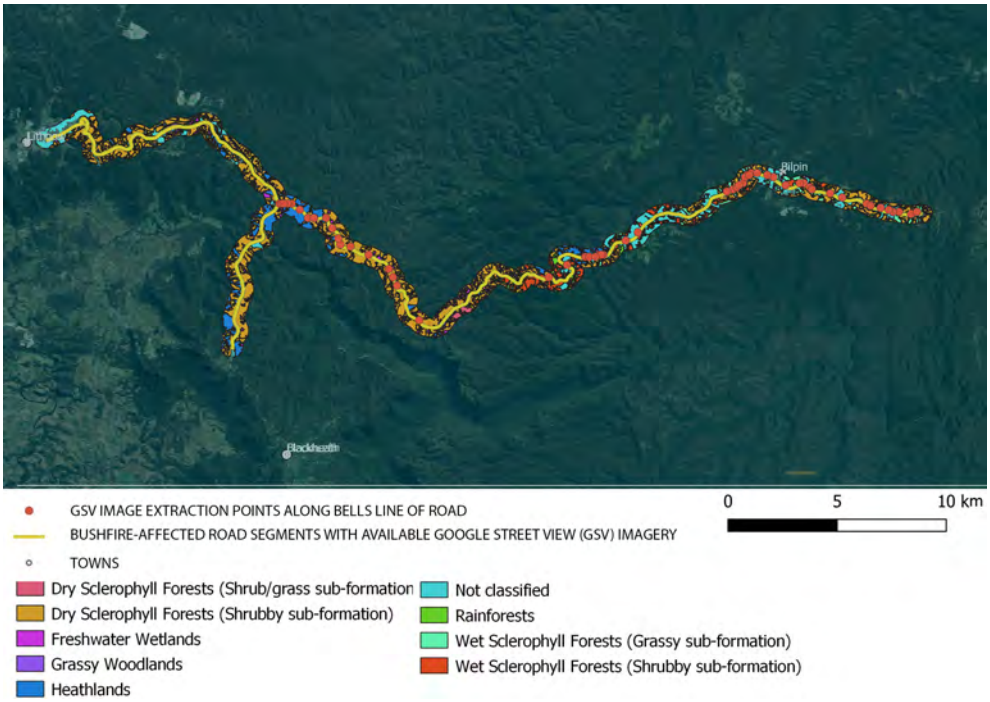

Fig. 3: NSW vegetation communities (SVTM) along Bells Line of Road, providing ecological context for roadside species analysis

Plant species were identified using a semi-automated workflow combining machine-assisted recognition with manual verification. Google Street View images from pre-fire, fire-year, and current conditions were processed using the Plant.id (Kindwise) API to generate candidate species detections for both the left and right sides of the road. Automated outputs, based on visible morphological characteristics, were manually reviewed to remove misclassifications, merge duplicate detections, and exclude low-confidence identifications, following emerging practices in street-level, species-specific vegetation analysis (HU et al 2025).

Given the reliance on street-level imagery and the absence of field surveys, species identification was not treated as a definitive floristic inventory. Instead, the approach prioritised consistency and comparability across time and space. Validation was undertaken through cross-comparison of detections at spatially fixed points across all three periods and by checking ecological plausibility against the NSW State Vegetation Type Map (SVTM) dataset (NSW DEPARTMENT OF PLANNING AND ENVIRONMENT 2022), which provides spatially explicit vegetation community classification across the state. Along Bells Line of Road, mapped vegetation communities are predominantly classified as dry sclerophyll forest, interspersed with woodland and regrowth shrubland types. Dry sclerophyll forests are characterised by tall eucalypt canopy species with a shrubby or grassy understorey and are generally considered fire-adapted ecosystems. This ecological context provides a baseline for interpreting post-fire structural change observed in the street-level imagery (Figure 3). Species results

were therefore interpreted at the level of dominant and visually legible vegetation, allowing patterns of species disappearance, persistence, and replacement to be analysed as indicators of structural and perceptual change along the roadside rather than precise taxonomic records.

2.3 Sky Openness Percentage

Sky openness was measured as the proportion of visible sky pixels within each street-level image and used as a proxy for canopy density and vertical vegetation structure as experienced from the road. For this study, sky openness was calculated manually for 56 spatially fixed roadside points using Adobe Photoshop, where sky areas were selected with the Magic Wand tool and quantified as a percentage of total image pixels. Measurements were undertaken consistently for pre-fire, fire-year, and current images, and separately for the left and right sides of the road.

This metric is interpreted as a perceptual and structural indicator rather than a conventional ecological density measure. It captures changes in enclosure, light, and exposure resulting from canopy loss and uneven regrowth, making bushfire disturbance and recovery legible at a human-eye level. When analysed alongside species detection and vegetation community mapping, sky openness provides a robust means of tracing how bushfire reshapes the spatial experience of roadside landscapes over time.

3 Results: Bells Line of Road

3.1 Sky Openness

Across the full set of 56 sampled roadside points, sky openness increased markedly following the 2019-2020 bushfire and has remained elevated at many locations, indicating a persistent alteration of roadside canopy structure. Pre-fire sky openness ranged from 1.4% to 50.3% (median 28.8%), increased during the fire year to a maximum of 54.6%, and in the current condition ranged from 0.3% to 61.1%, with many locations remaining more open than their pre-fire state. To make these changes legible at a human scale, a subset of representative points is examined in detail. On the left side of the road (Figure 4), sky openness at one illustrative location (33°30′14.4″S, 150°32′34.8″E) increased slightly from 48.6% in the pre-fire condition to 50.5% during the fire year, before partially closing to 36.4% in the current condition. This sequence reflects immediate canopy loss caused by the bushfire, followed by uneven and incomplete regrowth rather than a full return to pre-fire structure.

3.2 Species Detection and Turnover

Across the 56 roadside points, mean detected species richness showed little variation across time periods. The mean number of detected species per point was 2.7 before the fire, 2.8 during the fire year, and 2.9 under current conditions. While overall species counts remained similar, comparison across time periods revealed notable species turnover. In the current dataset, an average of 2.2 species per point were classified as missing when compared with earlier observations. Of the analysed points, 39% showed three or more missing species, 18% showed five or more missing species, and 11% showed no missing species.

These results indicate that although total detected species richness did not decline following the fire, changes in species presence were widespread across the study area.

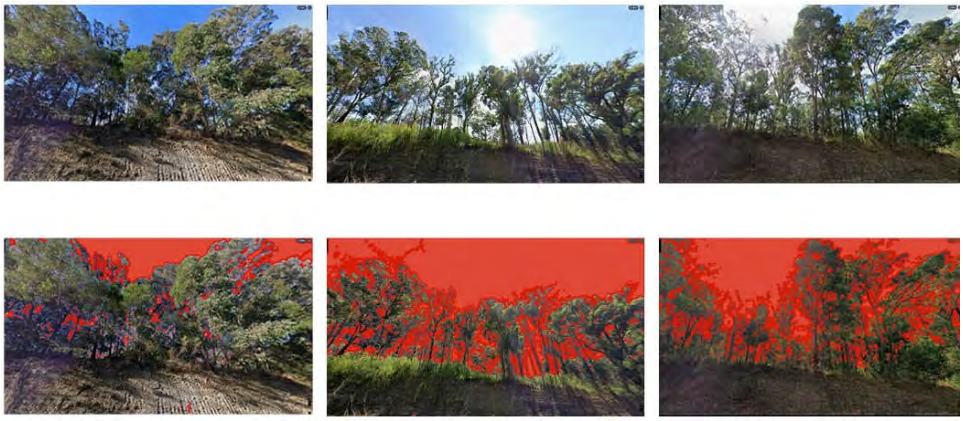

Fig. 4: Left roadside street-level views showing pre-fire, fire-year, and current conditions (top), with corresponding manual sky-openness calculations (bottom) illustrating canopy loss and partial post-fire recovery

3.3 Relationship Between Sky Openness and Species Change

Analysis across the 56 roadside points shows a clear relationship between sky openness and species turnover. Locations where sky openness exceeded 35% consistently exhibited higher numbers of missing species across time periods, reflecting substantial canopy loss during the fire year and persistent openness in the current condition. In contrast, points showing reduced sky openness during post-fire recovery, indicating partial canopy re-closure, displayed lower species turnover and greater continuity with mapped vegetation communities. While overall species richness remained relatively stable across pre-fire, fire-year, and current datasets, shifts in sky openness were associated with changes in species presence rather than total species counts. This suggests that sky openness mediates how species turnover and ecological change become visible at the roadside scale through street-level imagery, roadside scale structuring how ecological change becomes legible from street-level imagery.

4 Discussion

This study set out to examine how bushfire reshapes roadside landscapes through measurable changes in sky openness, and how these changes relate to vegetation communities and species structure over time. Using approximately 56 spatially fixed observation points per roadside, sampled consistently across three temporal conditions (pre-fire, fire year, and current), the analysis demonstrates a repeatable, street-level methodology for reading landscape transformation along linear infrastructure corridors impacted by disturbance. While applied here to Bells Line of Road following the 2019-2020 bushfires, the discussion focuses on the methodological implications of this approach for landscape architecture practice more broadly.

4.1 Magnitude and Persistence of Sky Openness Change

Across the corridor, bushfire caused a sharp and widespread increase in sky openness, reflecting extensive canopy loss and vertical structural disruption. At most points, sky openness

rose markedly in post-fire imagery and, although some recovery is evident, current values generally remain higher than pre-fire levels, indicating incomplete canopy reformation four to five years after the 2019-2020 fires. Only a small number of locations have returned to conditions comparable with pre-fire enclosure.

Despite local variation by vegetation type and roadside condition, this pattern was consistent across the study area, underscoring the long-term spatial legacy of bushfire along roads. Methodologically, the consistency of these changes highlights sky openness as a robust and transferable indicator derived from street-level imagery, applicable to other linear landscapes where canopy structure shapes spatial experience without relying on site-specific ecological surveys.

4.2 Vegetation Community Differences in Recovery Trajectory

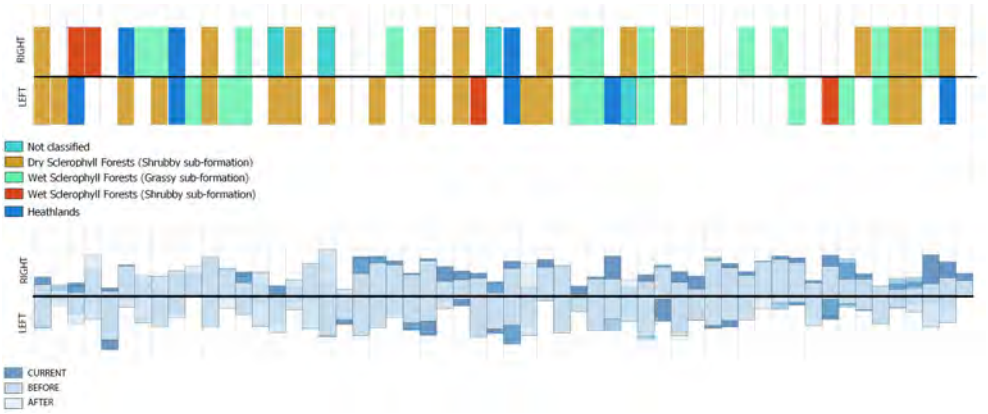

Fig. 5: Vegetation communities and associated sky openness patterns showing differing post-fire recovery trajectories along the roadside

Vegetation community emerged as a key factor shaping post-fire sky openness and recovery. Dry sclerophyll forest sites showed the largest increases in sky openness and the slowest return toward pre-fire conditions, with canopy gaps persisting in recent imagery. Shrubland and regrowth-dominated communities exhibited smaller increases and faster reductions in sky openness, driven by rapid low- and mid-storey regeneration, while woodland and mixed forest types showed intermediate and more variable responses (Figure 5).

These patterns indicate that recovery is not uniform when assessed through structural or perceptual metrics. Although dry sclerophyll forests are fire-adapted, their tall canopy structure makes them prone to prolonged openness, particularly along roadsides where exposure and maintenance intensify canopy loss.

4.3 Species Structure and Sky Openness

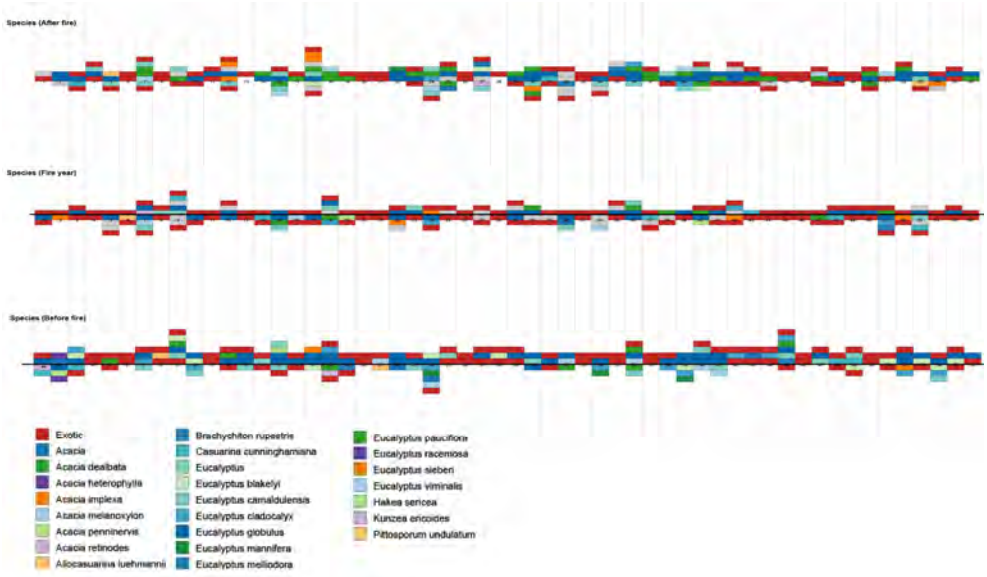

Fig. 6: Species detections at fixed roadside points across pre-fire, fire-year, and current conditions, illustrating species turnover and functional vegetation change following bushfire

Species detections were interpreted cautiously as indicators of dominant vegetation structure rather than precise floristic records, with clearly misidentified exotic species removed or grouped as "exotic" to reduce classification bias from automated plant recognition (Figure 6). When analysed at this structural level, species patterns closely aligned with changes in sky openness. Roadside points previously dominated by tall canopy species, particularly Eucalyptus and other sclerophyll trees, exhibited the largest and most persistent increases in sky openness following fire, reflecting extensive canopy loss and slow visual closure. In contrast, locations characterised by shrubs and mid-storey species – most notably Acacia-dominated regrowth – showed faster reductions in sky openness as dense understorey growth rapidly reestablished visual enclosure despite the absence of mature canopy height. These patterns indicate that vegetation functional role, rather than species identity alone, is a primary determinant of post-fire roadside structure and perceptual recovery.

4.4 Left-right Roadside Asymmetry

A further notable finding was the asymmetrical recovery between opposite sides of the road. Even within the same vegetation community and at similar chainages, left and right roadside points often showed different sky openness trajectories. In several segments, one side of the road exhibited consistently higher sky openness across all post-fire periods, while the opposite side showed faster closure. This asymmetry is likely influenced by a combination of factors, including slope orientation, aspect, prevailing wind direction during the fire, and

post-fire disturbance such as clearing or maintenance access. From a landscape architectural perspective, this reinforces the understanding of roads as heterogeneous corridors, where recovery unfolds unevenly and sequentially rather than uniformly. For road users, this results in alternating visual experiences of exposure and enclosure, producing a fragmented yet legible narrative of bushfire impact and recovery that unfolds dynamically along the journey.

4.5 Implications for Post-Fire Landscape Interpretation

The findings highlight a clear distinction between ecological regrowth and perceptual or structural recovery after bushfire. While many vegetation communities show biological regeneration within a few years, persistently elevated sky openness indicates that the spatial and visual character of roadside landscapes remains altered for much longer. For landscape architecture, this matters because roadsides are experienced landscapes that shape how bushfire, recovery, and resilience are perceived and remembered. Treating canopy openness only as a deficit to be rapidly closed risks erasing the spatial evidence of disturbance and the temporal depth of recovery. Instead, the results suggest that post-fire openness can be recognised as a legitimate and meaningful landscape condition, informing more nuanced and narrative-driven approaches to post-fire design and interpretation.

4.6 Methodological Reflections and Limitations

The study integrates datasets with differing levels of precision, combining quantitative sky-openness metrics, stable vegetation community mapping, and semi-automated species detection. Species identification from street-level imagery is necessarily limited and was interpreted cautiously, with emphasis on dominant and visible vegetation rather than exhaustive floristic accuracy. However, triangulating across these indicators allows consistent spatial patterns to emerge despite uncertainty at the species level. Future research could expand the number of sampled points, extend the temporal range, incorporate additional perceptual metrics (such as colour or texture), or selectively validate results through field surveys, strengthening the framework without undermining its scalable, street-level focus.

5 Conclusion

This paper shows how digital, street-level analysis can reveal ecological recovery as a spatial and temporal narrative rather than a fixed end state. By integrating Google Street View imagery, sky openness, species detection, and vegetation community data, it develops a replicable framework for reading landscape change along linear infrastructure corridors.

Although applied to a bushfire-affected roadside, the value of the work lies in its methodological contribution. The approach is transferable to other contexts where landscape change is gradual and experienced sequentially, such as post-disaster recovery, vegetation succession, urban canopy loss, or infrastructure-driven transformation. Roads are reframed as spatial archives through which landscape processes become visible over time.

The study positions landscape architecture not as a producer of new ecological datasets, but as a discipline capable of translating complex environmental change into legible, comparable, and communicable spatial narratives. By treating disturbance as an ongoing condition rather than an anomaly, the paper contributes a framework for interpreting dynamic landscapes in ways that support more adaptive, resilient, and design-relevant practice.

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Indicating Infiltration – Monitoring Plant Migration in Rural Coastal Towns

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Abstract: The focus of this paper is on the capacity of remotely sensed data and spectral signature libraries to track indicator species of saltwater infiltration in coastal zones. Current challenges in large-scale mapping of wetland migration include low frequency data collection as well as limited sensing techniques and data types. The use of spectral libraries, neural network analysis and both aircraft and Unmanned Aircraft Systems (UAS) collected data can enable Landscape Architects to move beyond common wetland and coastal delineations to see and map nuanced and incremental coastal change through the migration of high marsh indicator species in small cities and towns. Mapping these changes is a vital aspect of planning and designing for coastal adaptation that more accurately reflects current conditions, projects future trends, as well as displays the variety of pathways enabling saltwater infiltration.

Keywords: Nature based infrastructure, monitoring, adaptive management, indicator species

1 Introduction

Marsh migration is one of the key indications of saltwater infiltration stemming from sea level rise in coastal zones. In open landscapes, these changes can be observed through the dieback of upland vegetation and the emergence of salt panne, the perennial dampness of soils in transition from non-hydric to hydric, and the migration of salt marsh species such as Sporobolus pumilus, and Iva frutescens. "… marsh halophytes appear to migrate gradually into tidal freshwater wetlands and open fields in response to sea level rise, as increased flooding and salinity allow them to outcompete non-halophytes" (McKown & Burdick 2024).

However, in urban environments, saltwater movement can be difficult to track. The infiltration of saltwater in low lying areas through the vadose soil zone as well as its tidal movement through drainage ditches can be temporally infrequent while exceedingly common across seasons to create substantial changes in plant and soil composition. In many common neighbourhood landscapes such as lawns, shrub gardens, ditches and feral lands, the slow and incremental creep of saltwater results in species in-growth and plant replacement, but often hidden by common maintenance practices such as mowing and pruning. Many lawns on marsh fringes often transition from common cool season grasses such as Poa pratense to marsh grasses such as Sporobolus pumilus and Panicum amarum without the property owner ever realizing they are maintaining a high marsh.

These subtle changes raise an important question for Landscape Architects working on coastal adaptation and resilience planning in rural regions – how do we map, baseline, assess, and plan in these changing landscapes where base data has scalar and temporal limitations that often miss important changes in the landscape? At the site scale, wetland delineation remains a reliable method of mapping, when commissioned at consistent intervals. This approach is often paired with monitoring wells in select locations to provide a high level of site-specific data accuracy but a low level of coverage. Yet, when working across an entire town or rural region, the primary resources for marsh mapping become more reliant on remote

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sensing techniques with geographic and temporal limitations. The United States Fish and Wildlife Service (USFWS) National Wetlands Index represents the "best available" widespread public repository, but is temporally governed by the resource limitations that dictate the frequency of data collection. The Emergency Wetlands Resource Act stipulates that "National Status and Trends data are collected using a survey-based approach carried out within 5,048 four square mile plots randomly distributed across the conterminous U.S…" to be published in the Wetland Status and Trends report (LANG et al.2024). So, while there is guidance ensuring that the plots for this reporting are collected each decade, the vast majority of collections are subject to available local, state or federal funding.

At the scale of towns and regions, the USFWS's "Wetlands Mapping Standards" guide the use of satellite infrared data at a 1-3m resolution with both supervised classification and manual entry to identify soil moisture patterns that correlate with the presence of a marsh (FEDERAL GEOGRAPHIC DATA COMMITTEE 2009). Yet, many of the features in coastal towns and farms, from yards to drainage ditches, are smaller than the average pixel size/ spatial resolution of National Wetlands Index data. The combined impact of low frequency collections with 1-3 meter infrared spectral data and hybrid classification techniques results in data that is frequently out of date and underrepresents the extent of coastal wetland complexes in urban environments.

Soil moisture is but one registry or indicator of marsh migration, and could be paired with another common early indication of marsh migration – salt tolerant or halophytic vegetation. However, species-specific identification is not possible with low resolution infrared data. This presents an opportunity for Digital Landscape Architecture to bring plants to the forefront of infrastructure planning and coastal adaptation monitoring by leveraging the migratory capacity of rhizomatous halophytic shrubs through the development of monitoring techniques that employ remote sensing to further expand the capacity to define marshes and their incremental migration. Currently, species-specific, large-scale monitoring techniques enabling Landscape Architects to focus on indication at the scale of site features impacted by regional hydrology are limited by gaps in technical and methodological development. A way forward exists in the methods identified in "Monitoring Plant Species for Nature-based Infrastructure Design" (LUEGERING & BASENER 2025), including data classified using a Fundamental Spectral Signature library and neural network modelling. To test these methods, Iva frutescens was selected as it represents one of only a few species at the high marsh fringe, whose saline sensitivity, capacity to migrate, and distinct spectral signature enables high fidelity matching using the aforementioned techniques.

2 Mapping High Marsh Species Migration

2.1 Context – Crisfield Maryland and the Delmarva Peninsula

With the Chesapeake Bay region, the Delmarva peninsula's glacial isostatic adjustment in combination with regional subsidence and sea level rise has resulted in some of the fastest global rates of land loss and marsh migration. Such changes put even greater pressure on the need for high spatial quality, high collection frequency data that effectively describes the shifting position of coastal saltwater marshland. The town of Crisfield Maryland typifies Chesapeake Bay facing municipalities of the mid bay – built in low lying areas and drained marshes, facing uncertain futures due to regular flooding and loss of viable developable land.

Ecologically, the plant composition of this region's marshes include an abundance of the high marsh fringe plant Iva frutescens.

2.2 Methodology

The work of the Urban Planning with Integrated Natural Systems (UPWINS) research project at the University of Virginia's Natural Infrastructure Lab focuses on both the adaptive management of plant species with strong phenotypic plasticity as well as the development of approaches for monitoring plants for nature-based infrastructure. Our studies on the monitoring of plants at the scale of infrastructure suggest that there are important subsets of data and methods of analysis that enable the identification of select plant species capable of indicating changes in coastal and riverine landscapes. Our approach relies on distinct differences in plant chemistry that can be registered through collections of nonvisible spectra. However, not all nonvisible spectral data is created equal – the time of year, health of the plant, environmental conditions including air quality and soils, as well as the type of spectral sensor all create complex variables. Our approach, referred to as "Fundamental Signatures" (LUEGERING AND BASENER 2023), considers how the creation of a large data set library of each plant's various parts collected over a period of time at multiple scales can take advantage of advances in machine learning/ neural network construction and remote sensing to collect, classify and map the desired species over time. "The Fundamental Signature approach of UPWINS focuses on thirteen species of plants…frequent temporal collections at all stages of a plant's growth cycle capture intrinsically unique elements of the plant that may enable statistically significant differentiation between other plants in a field condition. Each species selection is based on study of their principal physical traits, both visible (such as bloom and bloom time) as well as nonvisible (such as unique chemical composition) characteristics" (LUEGERING & BASENER 2025).

While the signature library is controlled lab-collected data, our method also requires field data sampling because field signature data has much more interference as well as variability from growing conditions. Initial results have shown that the pairing of relatively few field samples with a large, controlled library enables a neural network to "connect" and maximize data from different environments. The field data is sampled from the remotely sensed data (as will be described below), and so to ensure accurate pixel sampling we use Real Time Kinematic (RTK) survey quality mapping tools for our field work. This process of field identification and RTK point creation enables the establishment of regions of interest (ROIs), or pixel sampling of the target species that can be incorporated into the training data library processing to build linkages between spectral library data and the specific spectral data of a region or site of interest. Our project has built custom tools to enable the viewing, establishment and export of ROI data for neural network training. A further complication of this work is the calibration and atmospheric correction of remotely sensed hyperspectral data. Referred to as Hyperspectral Images (HSI) or "Cubes", this data can be imagined as a 3-dimensional raster, where each pixel contains composite spectra made up of hundreds of wavelength channels. Our lab has developed its own reflectance calibration method which uses multiple zones of one or more in-situ calibration tarps to help manage the noise that is common in HSI remote sensing. Once the HSI are calibrated, and the range of library and field training data has been aggregated, the final step in the process is the use of a customized neural network built on the TensorFlow infrastructure to train on a small subset (< 100) pixels from the library consisting of thousands of lab collected terrestrial signatures, reflectance calibrated

lab collected microscene data, and reflectance calibrated ROI pixels from field identified background and desired plant species data (LUEGERING & BASENER 2025).

2.3 Mapping and Analysis

The UPWINS project's focus on the impacts of sea level rise and saltwater intrusion into small towns on the Eastern Shore of Virginia and Maryland is supported by access to small family farms for UAS remote sensing as well as large scale piloted aircraft collections across the entire region. Work from the former, as represented in Figure 1, depicts a single HSI processed result for Iva frutescens (pink pixels) and a series of field collected RTK data points (white hexagons) our team created during a field observation visit. The points were an attempt to loosely walk the "Iva line", or the formation of upper marsh fringe, with the goal of verifying the accuracy of our analysis during post processing. The green false coloration is not indicative of any one species, but was used to provide graphic relief to a black and white 1 band underlay aerial. The seeming void at the middle of the image (around the reflectance tarp placed for the UAS fights) is a large stand of the high marsh species Sporobolus pumilus, slowly migrating from the tidal flats of Johnson Creek (noted in Figure 2).

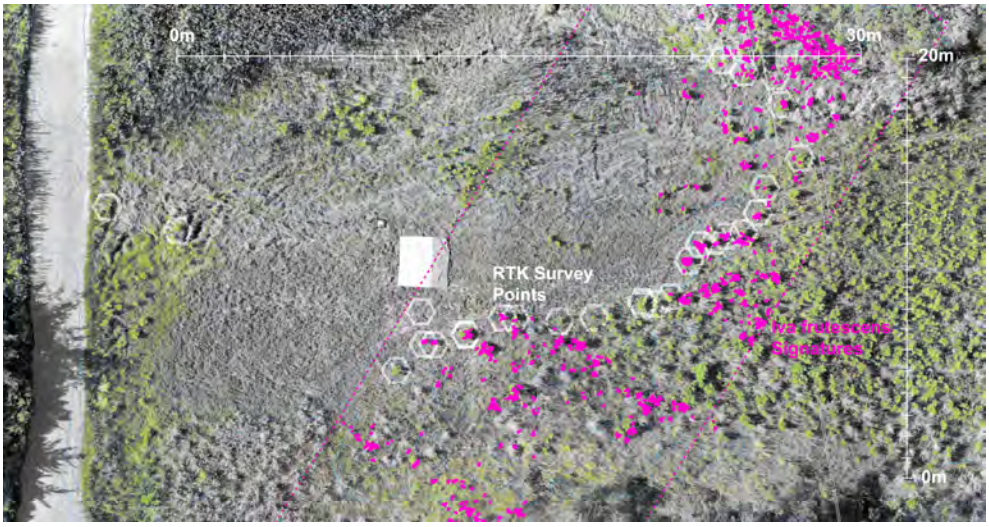

Fig. 1: Greenhead farm individual HSI cube with Iva frutescens (pink dots) mapped with UPWINS toolset. Sample plant locations (white hexagons) verified via field identification. HSI and Ortho images collected via UAS by Michael Luegering, April 2025.

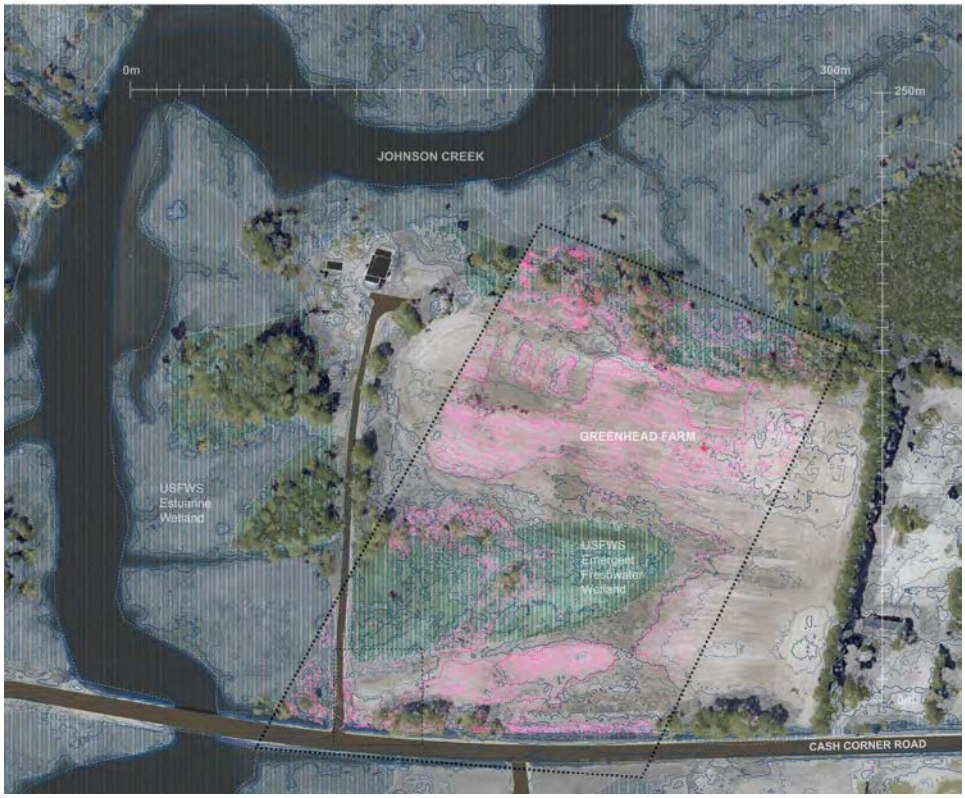

Fig. 2: The high marsh fringe in Greenhead farm, including Iva frutescens (pink pixels), has migrated well beyond the extent of wetlands defined by USFWS wetland mapping (blue and green hatches). HSI data collected via UAS by Michael Luegering with Underlay Ortho Aerial and USFWS wetland boundaries provided by the State of Maryland, April 2025.

Figure 2 is a composite of ~80 HSI from a single UAS flight in April of 2025 (including the HSI depicted in Figure 1), mosaiced together following neural network analysis and reclassification. The swaths of pink pixels indicate the locations of Iva frutescens and the formation of an upper marsh fringe – these formations have been enhanced in the image via pink dashed lines. These "Iva Lines" are the formations created by the slow creep of salt water over long tidal cycles and can serve as markers or indicators of this incremental change at both a very detailed small scale as well as large patterns when collected and analysed in large aggregations. The USFWS wetland mapping, hatched in blue for salt and green for emergent freshwater wetlands, provides a comparison of change and accuracy of marsh definition. Zooming out to Crisfield (Figure 3), we can observe similar changes, but in much smaller pockets of space such as side yards, front drainage ditches, wooded lots – all seeing the emergence of Iva frutescens beyond the zones denoted by the USFWS 2010's wetland mapping extents.

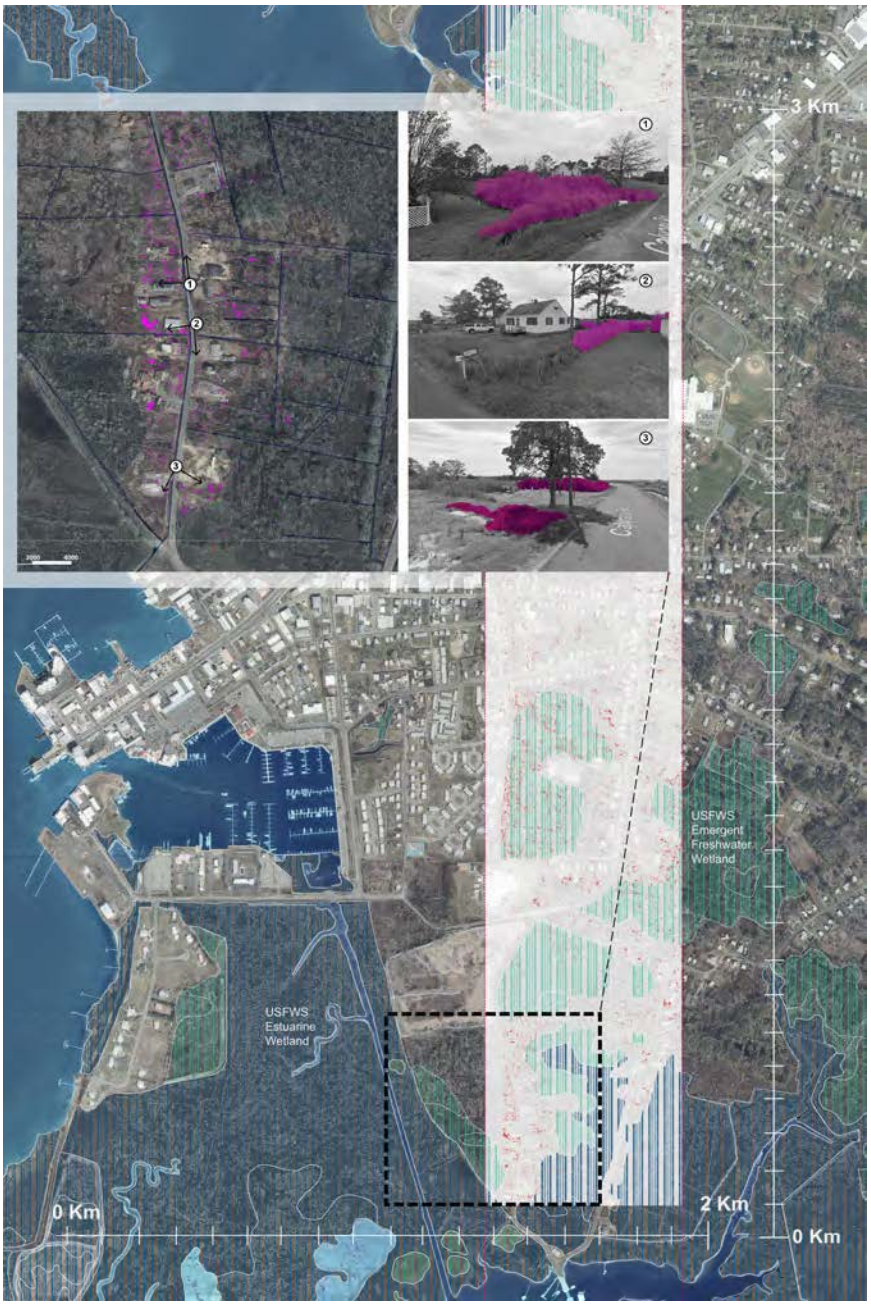

Fig. 3: Crisfield, Maryland – Iva frutescens (pink pixels) migration through inland neighbourhood streets via local storm drainage ditches. High marsh extent exceeds the most recent USFWS wetland mapping. Ortho image – State of Maryland, Ground level images – Google Street View, HSI data from piloted aircraft – SpecTIR. Data collected in April 2025.

3 Discussion

This round of UPWINS plant monitoring and mapping results worked to build upon our applied research on reflectance calibration, spectral library construction, UAS data collection and neural network analysis. Initial comparison with the USFWS's wetlands index data suggest that the mapping of indicator species can be additive to the analysis of marsh migration resulting from saltwater infiltration and general coastal zone change. The spectral signature approach's accuracy could likely be improved by engaging available USFWS data – improving indicator species identification through probabilistic analysis based on proximity of pixel-signature matching to USFWS delineated marshes. Discussion surrounding the development of this mapping methodology should focus on the following:

1) The value and impact of each data source into the neural network analysis, and how each data source can be further refined to improve outputs and results. This could include the addition of USFWS data to factor in the proximity to existing marshes.
2) The further comparison of results from this mapping with analysis from existing data sets such as AVARIS, ECOSTRESS, NEON. AVARIS's high altitude piloted aircraft hyperspectral remote sensing is currently limited in spatial coverage but offers the potential for regular, widespread >200 band HSI as well as ECOSTRESS's spectral library (NASA – JET PROPULSION LABORATORY). Based on AVARIS's technology, the National Ecological Observatory Network (NEON) focuses on plant community health.
3) For UAS-based mapping, comparisons from results of similar UAS collected HSI plant mapping as detailed in "Hyperspectral Classification of Plants: A Review of Waveband Selection Generalisability" (HENNESSY et al. 2020).
4) The methods for simplifying and expanding plant library construction to widen access to this mapping technique within the Landscape Architecture community.

4 Conclusion and Outlook

Landscape Architects are increasingly engaged in projects concerning rapidly changing coastal environments, where large scale nature-based infrastructure is a critical element of the design approach. Yet, the lack of current and accurate data demands new approaches that can effectively map changing conditions through the life of a project (and beyond, into adaptation). The methods under development in the UPWINS project show a path to site study and assessment that can engage plants as both critical elements of design and infrastructure as well as the indictors of change and trends in shifting landscapes.

Acknowledgements

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Repeat Multispectral Drone Imagery: A Case Study in Capturing Seasonal Change

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Abstract: This paper presents an exploratory research project in visualizing the seasonal change of meadows using repeat multispectral drone surveys and aerials. The research case study site is the *Alabama Meadows*, a series of meadow test plots within the southeastern United States. Meadows are characterized by their complex biodiversity of grasses and forbs, sensitivity to disturbance, and maintenance through prescribed fire and/or mowing. Often misunderstood because of their dramatic seasonal changes, the focus of this study seeks to promote deeper understanding of meadows through repeat photography. Repeat drone surveys using multispectral imagery (MSPI) were conducted over a single growing season in 2024 with the objective of capturing the seasonal shifts of meadows. MSPI was explored because of how the imagery can enhance the visibility of foliage through the reflectance of near-infrared light from chlorophyll-rich leaves, enabling detection of subtle changes in meadow composition. This study examines how landscape architects can harness MSPI to promote and enhance our understanding of seasonal changes in complex landscapes.

Keywords: Multispectral imagery, drone surveying, meadow ecology, repeat monitoring, aerial photography

1 Introduction

Since 2016, specialty drones with multispectral imagery (MSPI) functionality have become commercially available. These drones feature “multi-lens” cameras that include a near-infrared lens in addition to standard color lenses. A multispectral drone works by capturing the same vantage point with multiple lenses, with each lens filtering a range of wavelengths in the light spectrum. Assigning an additive color, often red, to the near-infrared image produces “false color” imagery that brightens and enhances the legibility of vegetation (LILLESAND & KIEFER 1994, 104). Within landscape architectural research, existing studies utilizing MSPI has focused on questions of species identification by spectral reflectance, and methods for creating detailed land cover classification within coastal, estuarine, and wetland sites (LUEGERING & BASENSER 2025, M’CLOSKEY & VANDERSYS 2022). Across those existing studies, a recurring challenge remains: how to effectively monitor the dynamic qualities of complex landscapes to document change over an extended time. The most well established method involves repeating MSPI drone surveys at consistent intervals – such as biweekly or monthly – a method called “repeat drone surveying” (MILLIGAN 2019, 21). Because time encompasses many elusive yet important qualities that landscapes interact with, drones have long been seen as potential tools for “change detection” (SANDERS 2016). By juxtaposing repeat surveys in a sequential format similar to frames in animation, researchers are able to read between images and produce rich documentations of landscape change and transformation (MILLIGAN 2019, 26).

The usage of MSPI in landscape architecture can be attributed to the growing availability of multiband aerial data from remote sensing programs such as the National Agriculture Imagery Program (NAIP) or Landsat 8 (LANDSAT 8 – NASA SCIENCE 2023, NAIP INFO SHEET 2023). Data from such sources are commonly available for public use as downloadable raster

files, which has promoted landscape architecture's role in ecological assessment and nature-based designs. But for this paper's exploration of meadows and grasslands, the applicability of such remotely sensed data becomes constrained by resolution: a standard Landsat pixel is 30 by 30 meters (900 m^2). When compared to the specific site of this research, which covers an area of 1641.7 m^2, a single Landsat pixel effectively aggregates 55% of the site into a single data point. As a result, detecting change over time loses plant-scale clarity and the phenological nuances. Additionally, research using such data will have no control on the specific year or month the data is collected. Given these caveats, acquiring MSPI using small unmanned aircraft systems (drones) is a compelling alternative. By allowing for on-demand imagery capture at any point within the growing season and higher resolutions down to the scale of the plant, multispectral drone surveying fills in a critical gap unachievable by current remote sensing programs. And whereas satellite imagery is limited to a nadir (top-down) point of view, drones allow for perspectival, oblique imagery that permit the observation of vertical plant structure.

Several obstacles have limited the adoption of MSPI drone surveying in landscape architecture. Repeat drone surveying involves multiple return trips to a project site over a sustained and extended period, requiring careful planning of resources, personnel and travel. Outside of landscape architecture, MSPI is most widely used as an analytical tool in the field of "precision agriculture", where crop health is evaluated based on maps visualizing the Normalized Difference Vegetation Index (NDVI) (HONRADO et al. 2017). Farmers use NDVI to evaluate crop health based on a principle that the chlorophyll in healthy plant leaves can absorb red light, while reflecting near-infrared light. In precision agriculture, NDVI mapping is considered an effective method for capturing overall patterns of plant health and productivity. But NDVI maps inherently oversimplifies plants as either healthy or stressed, flattening nuances related to seasonality or phenology. We believe landscape architecture operates in a more experiential, seasonal, and unpredictable context, making analytical tools such as NDVI overly technical for most practical use cases. The goal of this paper is not classification or quantification, but to broaden understanding of MSPI's potential benefits and to sustain its relevance despite the obstacles that limit its broader adoption in design practice.

Previous research in MSPI has mainly been situated within coastal and estuarine sites. A gap exists in its application towards grassland and meadow sites. Southeastern meadows are ladened with complex biodiversity and dynamic climate conditions, making them easily misunderstood due to their dramatic seasonal shifts. Thus, the unique contribution of this paper is demonstrating how repeat MSPI can help visualize the seasonal growth patterns of meadows. MSPI drone surveying is also explored as an interpretive tool, embracing the limitations of precision-focused technology and reframing the messiness of drone surveying as strengths rather than compromises. This reframing is explored of MSPI through the addition of aerial obliques as a new method for visualizing the spatial qualities of meadows.

In summary, the research presented in this paper has three objectives:

1) To visualize the seasonal growth patterns of a group of meadow test plots via drone acquired, repeat MSPI orthomosaics and aerial obliques.
2) To evaluate and discuss the shortcomings limiting broad adoption of MSPI.
3) To discuss the bigger role MSPI can play in landscape architectural practice, sustaining its relevance in a discipline that risks underutilization of MSPI.

2 Case Study Site

The case study site for this repeat MSPI project is the *Alabama Meadows*, a group of six meadow test plots located within a private demonstration forest in Auburn, Alabama. Originally installed in 2020, *Alabama Meadows* was born out of a curiosity to better understand southeastern meadows through intensive hands-on fieldwork, curated maintenance regimes, and ongoing monitoring. The installation features six meadow test plots, each circular in shape and 45.72 m (150 feet) in diameter. Over the course of five growing seasons and counting, these plots have been maintained via prescribed burns, mowing, and weeding (HILL & KNOX 2020, ZHOROV 2023). For the repeat drone surveying project, three of the six plots were chosen to be monitored due to their unique contexts and meadow seed mixes:

- Plot-3 features a Blackland Prairie mix and Southern Tallgrass Prairie mix, with a prominent band of *Coreopsis* wildflowers across its center. This plot was chosen for its rich biodiversity, making it the ideal test site for observing phenological change. It was the only plot in the study unobstructed by tree canopy, allowing for complete aerial mapping by the drone survey. Aerial obliques were also captured, enabling direct comparison with orthomosaics for capturing seasonal change in the meadow. Due to its biodiversity and suitability for comprehensive aerial capture, Plot-3 was prioritized as the primary focus of the study.
- Plot-2 lies entirely within a longleaf pine forest and features a savanna-like meadow condition. Because of the overhead canopy of longleaf pines, automated drone mapping was not practical, and only aerial obliques were captured of this plot. This plot was included to test methods for documenting seasonal change under conditions that limit drone flight.
- Plot-1 includes an open area seeded with a shortgrass meadow mix and a partially shaded area with a woodland edge mix. This plot features a range of conditions characterized by disturbance and maintenance, mainly caused by the gravel access road that bisects the plot. Due to its partial tree canopy coverage, capturing the plot in its entirety using drone mapping was not feasible.

3 Methodology

3.1 Preliminary Method Testing

During a preliminary trial phase, the feasibility of repeat MSPI surveying at the *Alabama Meadows* was explored using low-cost, do-it-yourself methods: a Parrot Sequoia multispectral camera was attached to a Phantom 4 (DJI) via a 3D-printed custom mount. Such makeshift methods are common starting points for multispectral drone research projects (KOPAČKOVÁ-STRNADOVÁ et al. 2021). Multiple surveys of Plot-3 were conducted between May 2022 and March 2024. The resulting datasets were used to generate false-color maps emphasizing meadow growth patterns and successfully captured a full growing season. While these results demonstrated that multispectral surveying could be conducted using do-it-yourself techniques, the approach also revealed limitations in reliability and reproducibility due to the improvisational nature of the methods. Limited access to fabrication tools, the required 3D modelling skills, and imprecise assembly procedures led to workflow inefficiencies and an overreliance on trial and error. These lessons directly informed the second phase of re-

search, which transitioned to using a Mavic 3 Multispectral (DJI). With a multispectral drone ready to operate "out-of-the-box", workflows were streamlined, enabling more reliable, consistent, and replicable surveys while flattening the learning curve.

3.2 Repeat MSPI Survey Workflow and Data Processing

For the second phase of research, ten repeat surveys of Plot-3 and Plot-1 at *Alabama Meadows* were conducted between June and October 2024. Survey dates were June 5, June 19, July 3, July 17, July 31, August 18, September 3, September 24, October 10, and October 20. This timeframe emphasizes the peak growing season for the meadows while also capturing the transition to fall dormancy. All surveys were conducted at midday (approximately 10:00 a.m. to 2:00 p.m.) to minimize shadow length under the noon sun and to maintain even light exposure, although consistent lighting conditions were difficult to achieve, as discussed later. Using the automated mission-planning application Dronelink, flight missions were planned at a consistent altitude of 12.2 meters (40 feet) above ground level, low enough to capture details that would reveal distinctive plant form. Since the work did not require centimeter level precision in terms of dimensional accuracy, the surveys relied solely on the integrated GPS metadata from the Mavic 3 Multispectral to align photos for processing and did not use ground control points.

Table 1: Automated mission parameters configured in Dronelink. Although the software utilizes the "Mavic 3E-Wide" camera profile for flight planning, this setting is compatible with the Mavic 3 Multispectral drone and was used for all site captures.

Plot	Camera	Altitude	Front Overlap	Side Overlap	Ground Sample Distance	Max Speed	Total Time	Photos
Plot – 3	Mavic 3E – Wide	12.2 m (40 ft.)	75%	75%	0.33 cm/px	5.8 kmh	14:36	374
Plot – 1	Mavic 3E – Wide	12.2 m (40 ft.)	75%	75%	0.33 cm/px	5.8 kmh	7:57	199

Each drone snapshot resulted in a standard RGB image (.jpeg) in addition to red, green, red-edge, and near-infrared multispectral images (.tif). The images were uploaded to the photogrammetry software PIX4D Fields to generate high resolution orthomosaics (0.24 in/px), then exported as a TIFF raster file. Using ArcGIS Pro, false-color maps were created by assigning the near-infrared band to the red channel, and the red band to both the green and blue channels, producing false-red orthoimagery that highlights meadow foliage. Clarity was further enhanced by overlaying the same orthomosaic rendered with the red band in all three channels (red, green, and blue) on top of the false-color layer and blending it using the 'Lighten' mode.

In addition to the orthomosaics, near-ground aerial obliques of Plot-3, Plot-2, and Plot-1 were captured from a consistent vantage point. The Mavic 3 Multispectral was centered on a marked ground location, flown to an altitude of 12.2 m (40 ft.), and held stationary while multiple angles of each plot were captured for stitching into panoramic images. Obliques were captured as both color photos as well as multispectral bands. The multispectral bands were composited in Adobe Photoshop to produce panoramic false-color oblique images. These obliques provided a visually dramatic means of interpreting meadow seasonal change, offering a three-dimensional perspective of meadow foliage and form (Fig. 1).

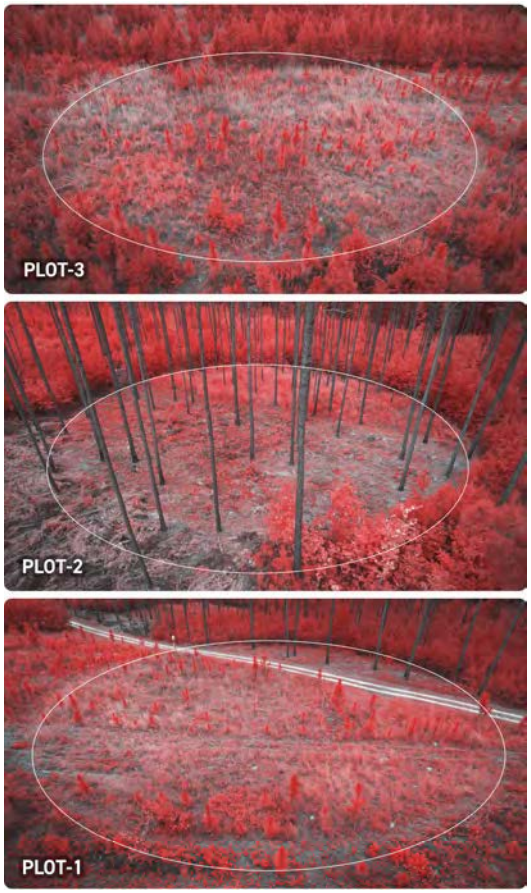

Fig. 1:
Multispectral aerial obliques for Plots 3, 2, and 1 captured on September 3, 2024

4 Results

The outputs of the repeat surveying project successfully demonstrated the potential of MSPI to capture change over time. When presented sequentially, the seasonal dynamics of meadow senescence become more legible in multispectral imagery than in standard color imagery (Fig. 2). This is due to the pronounced contrast captured as meadow foliage shifts from vibrant greens in early summer to muted yellows and browns in fall. In color imagery, these transitions often appear indistinct, as the hues of grasses entering dormancy blend with surrounding vegetation and soil (Fig. 3). Multispectral imagery, by contrast, enhances differentiation between foliage and ground through variations in near-infrared reflectance, rendering seasonal transitions more visually clear. Surveys conducted during the early fall month of September, when there is a high volume of grasses entering dormancy, were particularly dramatic for visualizing meadow change.

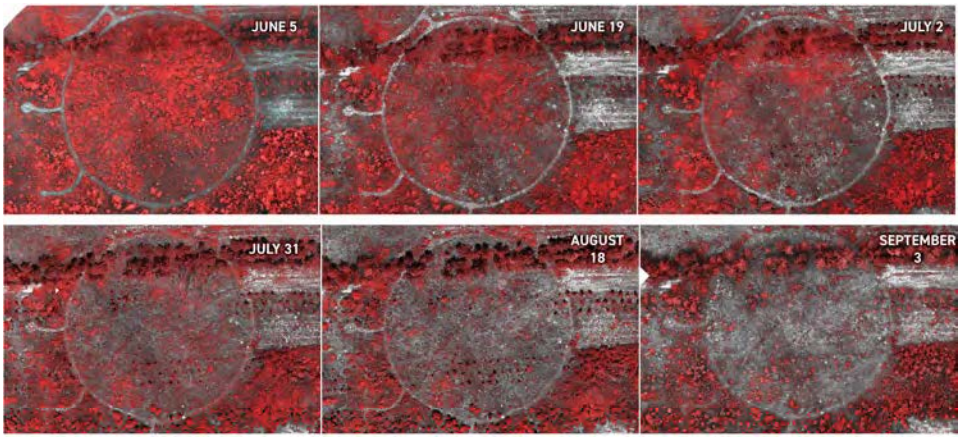

Fig. 2: Sequential arrangement for a selection of orthomosaics from Plot 3

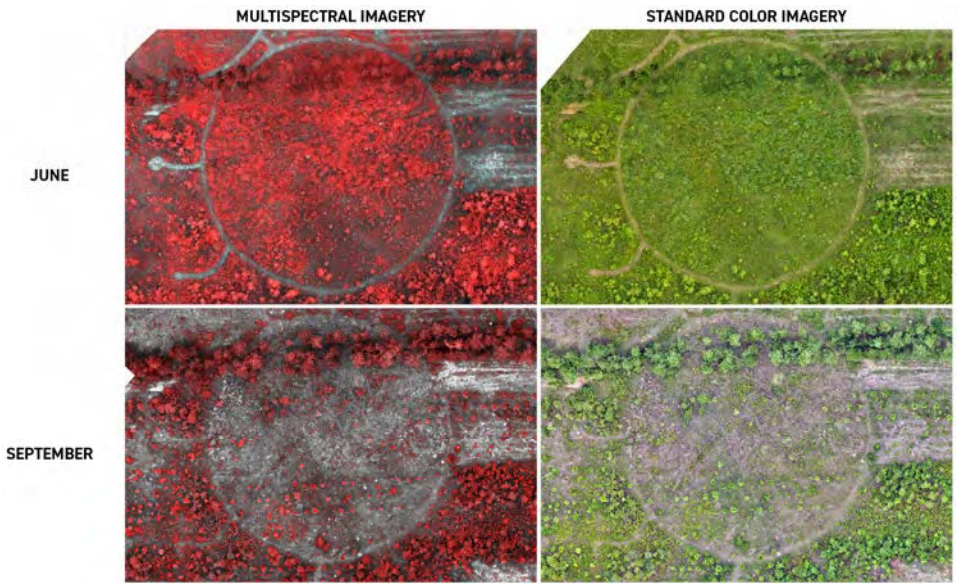

Fig. 3: Comparison of June and September orthomosaics for Plot-3

Oblique aerial imagery supported these findings, offering additional perspective into plant growth as grasses became taller and denser. A notable result emerged in Plot-2, the savanna condition, where multispectral imagery sharply distinguished groundcover vegetation from the trunks of longleaf pines. This clarity was further enhanced by the ability of near-infrared reflectance to illuminate shadowed areas, revealing groundcover that appeared dark or obscured in standard color imagery (Fig. 4).

Fig. 4: Oblique aerial panorama of Plot-2 taken September 3, comparing a standard color image (left) with multispectral false-red image (right)

5 Discussion

The seasonal multispectral surveys of *Alabama Meadows* provided a few key insights into the working methods required to engage with MSPI, providing direction for how landscape architects might best apply MSPI in research, practice and pedagogy.

5.1 Visualizing Seasonal Growth Patterns

MSPI is best used as a tool for intentional repeat surveying or repeat aerial photography. While single day multispectral images offer intriguing snapshots in time, the strength of the technology ultimately exists in revealing temporal dynamics that landscape architects contend with such as seasonal growth, decay, and regeneration. This lesson became clear when compiling the imagery – single multispectral surveys of each test plot proved less substantive as datasets without the ability to compare them over time. As such, planning for repeat surveys should be integral to the rationale for deciding whether to use this technology. Because MSPI enhances the visibility of plant material, it can be invaluable for projects requiring detailed mapping of vegetation, particularly in complex sites. For example, practitioners could use multispectral orthomosaics to verify planting plans during installation, confirming the accuracy of implementation, the success of early establishment, and the ongoing performance of the landscape. However, because the near-infrared light reflectance measure by MSPI can be highly variable, it is limited in its ability to translate that data into reliable plant identifications. In meadow landscapes, grasses may exhibit low chlorophyll reflectance in fall and winter due to seasonal dormancy rather than ecological stress. Existing research on evaluating grasslands through airborne sensing has suggested using a “spectral diversity” approach to estimate biodiversity (GHOLIZADEH et al. 2019). Even at high resolutions, MSPI is best used to provide a “big picture” view, which should be complemented with in-person ground truthing and fieldwork verification.

5.2 Broadening Adoption of MSPI

One of the main barriers to broader adoption of MSPI in landscape architecture is the logistical challenges of repeat surveying, which undermines the return on investment for such a program. Despite the efficiencies that drone technology provides, they do not resolve human practicalities involved with repeat site monitoring. Budget constraints, travel demands, scheduling conflicts, unpredictable weather, and the need for a licensed drone pilot can easily derail even the most carefully planned monitoring efforts. Existing MSPI research, typically produced by university-based landscape architecture labs, also acknowledge the cost constraints of repeat drone surveying (M'CLOSKEY & VANDERSYS 2022, 30).

Process and workflow dissemination thus becomes essential. The research at *Alabama Meadows* involved months of trial and error, with several drone surveys yielding flawed or unusable data. Each setback led to process adjustments, gradually refining the workflow until it consistently produced reliable results. However, as the workflow became more complex, transferring this knowledge to others proved increasingly difficult, making knowledge sharing a significant challenge in the research. Integrating drone instruction into university classes could be a productive first step to broadening a base of future practitioners with the knowledge to work with drones and MSPI. Other potential responses could include a stronger presence at conferences that encourage "talking shop" in formats such as live demonstrations, workshops, and continuing education classes. While written publications remain important, skill-based research methods ultimately benefit most from hands-on training.

5.3 Implications for Practice

To sustain the relevance of MSPI in landscape architectural practice, it should be positioned as a tool that supports both analytical and creative modes of work. On the analytical side, one strategy is to create incentives for repeated site visits and monitoring by standardizing MSPI within post-construction evaluation and performance metrics. Integrating MSPI within these common practices helps justify the investments required for repeat surveying

At the same time, MSPI faces underutilization due to its reputation as only an analytical tool. The oblique imagery captured at *Alabama Meadows* demonstrates the potential for MSPI to be positioned as an interpretive tool, one that supplements conventional landscape aerial photography with compelling false-color imagery capable of revealing the phenological qualities of landscapes. Promoting less rigid, more interpretive uses of MSPI may help reduce analysis paralysis and make the technology feel accessible, worthwhile, and inspiring for designers.

6 Conclusion

Landscape architects are in a unique position to build on the limitations of MSPI research, which tends to oversimplify vegetation as either healthy or stressed and overlooks natural seasonal variation. As the discipline continues to engage digital technologies, MSPI presents a promising bridge between remote sensing and the qualitative ethos of design practice. Its capacity to reveal vegetative growth patterns over time invites new ways of perceiving the impact of landscape architecture. However, without shared knowledge, the technique risks

remaining underutilized. Disseminating accessible workflows, case studies, and best practices will be essential to advancing the integration of MSPI into both design research and professional application.

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Visualising the Invisible: Drawing Attention to Temporal Patterns in Spatial Dynamics

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Abstract: *Visualizing the Invisible* presents a seminar-based course framework that integrates sensing, temporal resampling, and AI-assisted salience mapping to reveal dynamic processes that exceed human perceptual limits. Drawing parallels between transformer-based models of attention and landscape design as a relational practice, the work reframes form as the provisional outcome of intensive differences rather than static geometry. Through time-lapse imaging, frequency shifting, and abductive computational modelling, students construct salience landscapes that render environmental transformations and events perceptible. The paper contributes a reproducible workflow that expands landscape architectural representation and design agency toward temporal, process-based engagement with dynamic environments.

Keywords: AI-assisted visualisation, salience landscapes, temporal resampling, environmental sensing, emergence, spatial dynamics

1 Introduction

'Language can no longer describe the world in which we live. With antique ideas and old formulas, we continue to describe a world that is no longer present.'

Godfrey Reggio, director of Koyaanisqatsi, 1982

As computational technologies redefine how we perceive and construct the world, the image, now entangled with numerical code, simulation, and algorithmic modelling, supersedes the word as the primary medium of design. Within this cultural and epistemological shift, artificial intelligence, remote sensing, and digital visualisation are transforming how we sense, conceptualise, and materialise landscapes.

Just as AI's structure-forming transformer mechanisms reshape the landscape of language by modelling patterns of "attention" across sequences, designers reshape the physical, atmospheric, and cultural terrains we inhabit, revealing that all meaning, whether it be linguistic or spatial, emerges from how elements relate to one another across time and space.

This paper presents a seminar-based framework for visualising the temporal rhythms and spatial gradients that shape our environments. Using image sensors (film and still images), AI-assisted abduction, and drawing, the course extends human perception to generate new forms of spatial awareness and design agency. In doing so, it addresses landscape architecture's perceptual limitations regarding temporal dynamics and contributes to digital landscape architecture by formalising a reproducible workflow integrating temporal resampling and AI-assisted salience mapping into design pedagogy.

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2 Theoretical Framework

2.1 Attention, Temporality, and Form

All forms have an "architecture that is an arrangement of material in space over time, determining their shape and behaviour" (WEINSTOCK 2010) in a continual becoming. Each is a palimpsest of conditional processes, flexible and adaptive, shaped by visible materials and invisible gradients where forces give rise to flows. Following DeLanda's distinction between extensive and intensive space (DELANDA 2005), form is never static but the material registration of forces, what Kwinter calls "a network of enveloped material processes" (KWINTER 1992), a complex temporal and material manifold of differential space.

Transformer-based AI models construct meaning by organising relations of "attention" across sequences. Analogously, landscape architects engage with environmental fields by attending to relationships among elements distributed in space and time. Both systems, linguistic and spatial, generate meaning through relational patterning, suggesting a shared scaffolding between cognition, perception, and landscape architectural design.

Human perception operates within narrow temporal frequency bands – roughly 1 to 30 Hz – missing both rapid fluctuations and slow environmental transformations. By frequency-shifting data, compressing imperceptibly slow processes and expanding fleeting events, environmental signals can be remapped into perceptible windows, creating "salience landscapes" that expose hidden patterns in environmental systems. Drawing attention to parallel events across multiple temporal scales serves as both a sensorium and a framework, expanding what we perceive, how we relate to different time scales, and how we might respond to them.

In the course, spatial data (film) was resampled to highlight emergent flows, feedback loops, and constraints. Students derived salience heatmaps from these transformed signals, grounding abstract processes in measurable phenomena while developing new forms of environmental literacy and design agency. The work demonstrates how a reconceptualisation of time and space can inform responsive approaches to the built environment, engaging material and temporal dimensions through sensed and simulated landscapes.

2.2 Perceptual and Temporal Limits

Traditional representational techniques in landscape architecture limit the capacity to capture multi-scalar temporal dynamics. Slow processes unfold too gradually to be perceived in real time, while rapid events elude the human sensorium altogether. Consequently, critical environmental patterns remain hidden, constraining ecological understanding and design innovation.

Computational sensing and visualisation technologies address these perceptual blind spots. By shifting environmental signals into perceptible temporal bands, designers can construct salience landscapes that reveal previously invisible structures and relationships. This reframes the concept of a "site" as a range of spatio-temporal events, expanding both analytical and imaginative engagement with environmental systems.

In the course, students applied time-shifted sensing to plant growth cycles, hydrological shifts, and atmospheric light variation, producing layered salience maps that revealed environmental feedback loops. These mappings demonstrated how computationally mediated perception can uncover the latent dynamism of seemingly static environments.

3 Methodology

3.1 Computational Sensing and Temporal Resampling

The approach integrates environmental sensing, AI-assisted analysis, and time-based media to construct new perceptual frameworks for landscape.

Data Capture

Students employed multispectral time-lapse film to observe landscapes as active computational processes, treating recordings as "execution logs" that reveal how intensive differences, such as temperature gradients, moisture differentials, generate extensive forms such as channels, vegetation patterns, and atmospheric textures.

Temporal Remapping

By adjusting temporal intervals, students discovered critical points and phase transitions where intensities approach thresholds that trigger structural reorganisation.

AI-Assisted Pattern Detection

Transformer-based AI models were deployed to make visible salient patterns, feedback loops, and emergent flows within the transformed data. These processes augment human perception by locating structures across scales and timescales beyond direct human experience.

Salience Mapping

The resulting film (data) was visualised as dynamic overlays, highlighting zones of intensity, constraint, and flow. Through these steps, environmental signals were transformed into perceptually accessible and analytically rich landscapes, opening new opportunities for reading, interpretation, and design response.

3.2 Conceptual Frameworks

The conceptual framework for this course draws on philosophical and systems-theories that understand landscapes not as fixed objects, but as dynamic, relational processes unfolding across space and time. Following Deleuze and Guattari, systems are defined not by what they are as stable entities, but by what they do: how they mobilize forces, channel flows, and continuously undergo processes of territorialization and deterritorialization. This emphasis on action and becoming shifts attention away from static form toward fields of intensity and assemblages of interacting elements whose relations are always provisional. Manuel DeLanda extends this perspective by articulating a critical distinction between intensive and extensive measures of space, providing a materialist account of how form emerges. Extensive properties such as length, area, volume, and geometry describe spatial outcomes that can be subdivided without altering their qualitative character. Intensive properties, by contrast, are differences in density, velocity, or concentration that cannot be divided without losing their meaning and function as the generative drivers of change. Landscapes, in this view, are not composed primarily of extensive forms but arise from the modulation of intensive differences that give rise to thresholds, phase transitions, and emergent structures. Form is thus understood as a temporary stabilization of dynamic processes rather than a final or primary condition. Systems thinking complements this ontology by framing landscapes as adaptive systems composed of interacting components, feedback loops, and emergent behaviours, where

global patterns arise from local interactions rather than top-down control. Bergsonian and Deleuzian conceptions of time situate these processes within a temporal framework that privileges rhythm, duration, and qualitative change over linear chronology. Time is not an external parameter acting upon space, but an intrinsic dimension of becoming through which intensities evolve and structures take form. Together, these frameworks establish a process-oriented understanding of landscape in which space, time, and form are inseparable, and where design operates not by imposing static configurations, but by engaging the dynamic conditions through which landscapes continuously come into being.

3.3 Pedagogical Extensions: Cinema as Laboratory for Time

A weekly film program complemented studio investigations, exploring cinematic techniques of time and perception, bridging moving-image thinking and environmental sensing.

Across experimental and narrative traditions, cinema has functioned as a laboratory for thinking time as a material, perceptual, and environmental condition. The films examined in this course are instructive for landscape architecture because they do not treat time as a neutral backdrop for events, but actively construct temporal fields through duration, repetition, and attentional modulation. In doing so, they offer models for understanding landscapes as dynamic, processual systems rather than static form.

Within the course, films foregrounded time as both subject and technique enabling counter-narratives of space while providing a repertoire of perceptual tools for engaging temporal structure. These approaches directly informed the development of salient landscapes, narrative frameworks, and visual strategies later adopted within the students' Transformer-based AI models.

Early experimental works by Gary Beydler foreground the camera as an instrument of perception, producing time through bodily movement and attentional focus rather than narrative action. Films such as *Hand Held Day* and *Pasadena Freeway Stills* operate at the threshold between stillness and motion, where minimal shifts in framing generate perceptible temporal effects. This sensitivity to micro-change parallels landscape practices concerned with gradients, thresholds, and microclimatic variation. In *Venice Pier*, repetition and extended observation allow environmental change to accumulate gradually, producing atmospheric temporalities analogous to tidal, seasonal, and infrastructural rhythms.

A more explicitly material conception of time emerges in works aligning cinematic duration with environmental and infrastructural processes. Robert Smithson's *Spiral Jetty* collapses geological time, entropy, and representation into a single temporal field, positioning landscape as an evolving condition shaped by erosion and fluctuation. Len Gittleman's *Building Gund Hall* similarly frames construction as a temporal process, revealing architecture as an outcome of sequencing, delay, and accumulation. Both resonate with landscape architecture's treatment of time as a design material through growth, decay, and maintenance.

Bruce Conner foregrounds time as rupture and recurrence. In *Crossroads*, milliseconds of nuclear detonation are expanded through repetition and multi-angle replay, transforming an event into an enduring temporal condition. Time here is not linear recovery but ongoing exposure, paralleling landscapes shaped by persistent risk or infrastructural violence.

Structural film practices further demonstrate how time can emerge from systems rather than representation. Ernie Gehr's *Eureka* and *Side/Walk/Shuttle* reveal time as an emergent prop-

erty of mechanical and optical constraints such as speed and repetition. This aligns with landscape approaches that treat hydrology, airflow, sediment transport, or ecological succession as computational processes operating across multiple temporal scales.

Narrative cinema contributes insights into experiential time. Andrei Tarkovsky's *The Mirror* constructs time as memory, where past and present coexist, while Béla Tarr's *The Turin Horse* renders time as exhaustion through duration and repetition. Both illuminate how time is unevenly felt across bodies and spaces rather than uniformly distributed.

Urban and planetary temporalities frame broader critiques of modern landscapes. *A Trip Down Market Street* captures the city as unregulated temporal flow, while *Koyaanisqatsi* exposes asymmetries between technological acceleration and ecological rhythms. Sharon Lockhart's *Double Tide* aligns human labour with lunar and tidal cycles, foregrounding landscape as a planetary system governed by nonhuman temporal regimes.

Together, these films provide landscape architecture with a repertoire of temporal models ranging from micro-perceptual instants to geological and planetary cycles. They demonstrate how time can be sensed, constructed, and made legible through representation, offering critical tools for designing landscapes as temporal fields shaped by flows, feedback, and rhythms that continue unfolding long after design intervention.

3.4 Landscapes as Execution Logs: Abductive Computational Rule Discovery from Time-Lapsed Observation

This research approaches landscapes not as static spatial configurations but as execution logs of ongoing computational processes, in which form records the cumulative effects of interaction, feedback, and asymmetry over time. Geospatial agent-based modelling (ABM) provides a productive computational framework for engaging this condition, as it operates through three foundational agent types that correspond directly to spatial data structures: fields that encode continuous spatial properties, particles that represent mobile entities, and links that define relationships, boundaries, and constraints (WILENSKY & RAND 2015, CROOKS et al. 2019). Each agent operates according to local rules, responding to its own state and to neighbouring agents across these types, allowing complex global patterns to emerge from localized interactions. When grounded in geographic data, such as topography, hydrology, or infrastructure, these models reveal how spatial organization arises through interaction rather than prescription, and how emergent form reflects underlying system dynamics.

Central to this approach is abduction as a mode of reasoning. First articulated by Charles Sanders Peirce, abduction infers the most plausible generative explanation for observed phenomena, working backward from effects to possible causes (PEIRCE 1931-1958). Unlike deduction, which applies known rules to predict outcomes, or induction, which generalizes from repeated observations, abduction begins with surprising or unexplained forms and asks what minimal set of rules could have produced them. This mode of inference is particularly suited to landscape systems, where channels, vegetation patterns, sedimentary structures, or atmospheric formations often emerge through processes that are distributed, nonlinear, and only partially observable. Rather than assuming the governing rules in advance, or relying solely on statistical regularities, abductive reasoning treats landscape form itself as evidence – an index of the processes that produced it.

Within this framework, abductive rule discovery in geospatial ABM treats observed landscapes as execution traces of an underlying computational system. In the course, students work with time-lapse data drawn from physical systems, such as the Emriver stream table (Figure 2) or field-based environmental recordings, to observe real trajectories through phase space (GUERIN & DOUGLAS 2025a). These time-based observations provide empirical material from which agent behaviours, interaction rules, and spatial asymmetries can be inferred. The resulting agent-based models are not deductive simulations derived from theoretical first principles, but abducted hypotheses: provisional generative mechanisms inferred from observed landscape dynamics. In this sense, simulation becomes a form of explanation rather than prediction, and modelling becomes a means of reasoning with environmental processes rather than abstracting them.

A critical role in this process is played by intensive asymmetries, which function as control parameters within the system. Intensive differences such as gradients of slope, moisture, velocity, or sediment concentration are expressed computationally as asymmetries within fields, particles, or the topology of links and boundaries. These asymmetries govern system behaviour, and when they reach critical thresholds, they drive the system through phase transitions that produce new spatial structures. The resulting emergent configurations are order parameters, or extensive forms, that register the material consequences of underlying forces. By adjusting the temporal resolution of sensing media, designers are able to identify the precise moments at which such reorganizations occur, revealing how extensive spatial form crystallizes from intensive dynamics.

The abductive workflow developed in the course moves iteratively between sensing, inference, and simulation. Multispectral time-lapse recordings capture the extensive evolution of forms such as channels or vegetative patches, while simultaneously encoding the intensive dynamics that drive their transformation. These recordings are treated as datasets mapping the system's movement through phase space, rather than as static documentation. AI-assisted

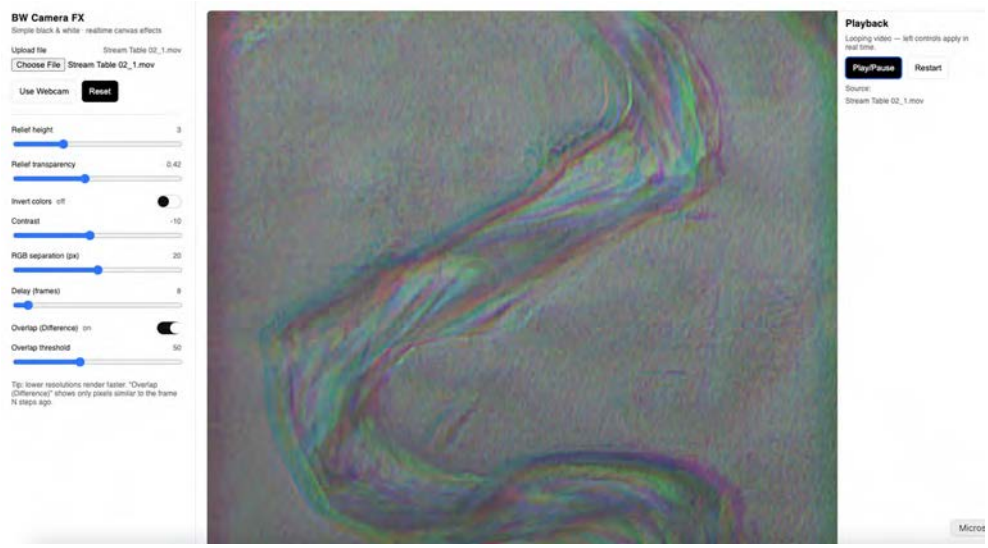

Fig. 1: Screenshot of "Repeating Days" interface by Gina Wenxuan Qiao

pattern inference is then employed to explore emergent behaviours and to propose candidate rules for agent-based models (GUERIN & DOUGLAS 2025b). In some cases, transformer-based models are used to translate observed hydrological patterns into computational fluid dynamics simulations – such as Lattice Boltzmann models – bridging empirical observation and numerical experimentation.
This methodology reframes the landscape site as an assemblage of space-time structures composed of interacting processes rather than fixed elements as evidenced in Gina Wenxuan Qiao's interface (Figure 1). It enables the discovery of latent system behaviours that are typically invisible to the human sensorium and difficult to apprehend through conventional representation. The use of large language models to generate interactive HTML and JavaScript-based analytical tools further accelerates this abductive cycle by lowering the technical threshold for environmental computation. In doing so, the approach aligns computational modelling with design inquiry, positioning simulation not as an external analytic layer but as an integral component of landscape architectural thinking.

4 Outcomes

Within the course, visualising the invisible refers to the deliberate construction of perceptual and representational techniques that render environmental processes legible across temporal and spatial scales that exceed ordinary human perception. In "Temporal Intensities" by Emi Kim (Figure 3) the "invisible" is understood not as immaterial or abstract, but as a set of dynamic forces, gradients, and relational processes of growth, decay, and feedback that operate beyond the temporal frequency bands of human vision and conventional design representation. In this work Emi reconceptualizes the landscape as a gradient of intensities from the least to most dynamic over time.

Landscape architecture has long engaged such forces implicitly, yet traditional tools privilege static form and spatial fixity, often obscuring the temporal dynamics through which landscapes emerge and transform. "Presence" by Gulsah Aygun Orhan (Figure 4) and Sanchit Agrawal project "Focus: Verify in Field" (Figure 9) addresses this limitation by treating invisibility as a problem of perception rather than absence, and by developing computational methods that translate environmental signals into perceptible temporal windows. In his work "behaviours, and disturbances form a shifting field rather than a fixed point of view".

Through image-based sensing, temporal resampling, and AI-assisted salience mapping, students construct representations that amplify differences, reveal thresholds, and expose emergent patterns within environmental systems. Slow processes are compressed, rapid events expanded, and distributed phenomena brought into relational focus. Hannah Lin's project "Afterimage Inscriptions" (Figure 2, 5, 6, 8) demonstrates that visualization here is not illustrative but operational, functioning as a mode of inquiry that produces new knowledge about landscape behaviour and performance. The aspiration of the work was to "counterpose spatial extensivity against the intensities of temporal events, a designed imaging system extracts fleeting motions into residual traces that fade, overlap, and persist."

As a contribution to landscape architecture, this work reframes representation as a form of perceptual infrastructure, a means of sensing, reasoning, and designing with time as an active material. By making dynamic processes visible, the approach expands design agency from the manipulation of static form to the modulation of flows, intensities, and temporal rhythms.

Public Life Study Datascapes that Visualize Space and Time

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Abstract: Public Life Studies (PLS) are widely used to evaluate public space, yet findings are often communicated through charts that flatten spatial and temporal nuance. This methods paper presents a hybrid workflow – community-based analog activity mapping, manual digitization, and algorithmic analysis/visualization – to generate "PLS datascapes". Using two temporary public space installations as case studies, we demonstrate how these visualizations reveal fine-grained spatial patterns and time-based behaviours that would remain hidden in conventional outputs, supporting more targeted design iteration and public communication of the social performance of public spaces.

Keywords: Public Life Study, data visualization, algorithmic analysis, social infrastructure, community-engaged scholarship, plazaPOPS

1 Introduction

This paper examines the use of community-based analog data collection methods, followed by data digitization and algorithmic computational tools, to create a type of visualization of Public Life Study (PLS) data that landscape architects can use to better evaluate the social performance of their designs. Going beyond standard PLS data visualizations, which typically result in pie or bar charts that communicate broad patterns and before and after comparisons about *who* was observed using a site, *what* people were observed doing, and *how* people were observed inhabiting a site, we outline a hybrid analog to digital method that results in the representation and analysis of PLS data that incorporates spatial and temporal dimensions. Allowing for a richer understanding of the public life occurring at a given site, and the impacts of a design or planning intervention, this method has the potential to enhance the design and evaluation of public spaces intended to function as social infrastructure.

The paper begins by discussing the typical outputs of the PLS method in research and practice. Next, based on research conducted to evaluate the social impacts of a temporary public space project designed by the authors, we outline the sequence of analog, digital, and computational methods we used for data collection, data digitization, data analysis, and data visualization, and showcase example datascape outputs. We discuss example spatial patterns that were revealed through this method, and to conclude, we reflect on the potential(s) of this method, and this type of visualization to communicate the spatial and temporal aspects of PLS data in an engaging and impactful manner.

2 Public Life Studies in Research and Practice

Environmental design evaluation (EDE) describes a broad research stream within landscape architecture and urban design concerned with the relationship between human experience and the designed environment, with intellectual roots that draw on multiple disciplines and

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5 Discussion

The integration of computational sensing and temporal resampling reframes the landscape as a complex spatio-temporal system rather than a static form. Expanding the perceptual field across temporal scales enables designers to:

- Develop new forms of environmental literacy, recognising dynamic processes typically overlooked.
- Engage with multi-scalar feedback systems to enable adaptive and responsive design strategies.
- Explore novel aesthetic and experiential modalities, where invisible processes become visible, legible, and designable.
- Apply AI for abductive rule discovery using pattern inference to explore emergent system behaviours.
- Develop a synthetic facility for analysing and composing dynamic spatial architectures grounded in flows, materials, and phenomena.
- Reconceptualise "site" as an assemblage of space-time structures, extending design to the temporal, sensory, and computational domains.

While several students relied on familiar tools like TouchDesigner and After Effects, others rapidly adopted LLMs such as ChatGPT and Claude to generate interactive HTML/JavaScript filters and machine vision algorithms after brief demonstrations despite no prior coding experience. This unexpected facility highlights how new AI systems are transforming design workflows, lowering the technical threshold for environmental computation and accelerating creative iteration.

These approaches also introduce critical challenges. Data interpretation requires caution to avoid reifying patterns as fixed truths. Translating sensed data into design propositions involves cultural, aesthetic, and ethical judgment, and the proliferation of digital images risks creating hyperreal landscapes, echoing Reggio's warning that imagery, if unexamined, can eclipse critical thought.

6 Conclusion

This research advances a shift from static representations of landscape to computationally mediated, temporally sensitive forms of visualisation. By integrating AI, digital sensing, and simulation, designers can extend perception into temporal scales previously inaccessible, revealing hidden patterns and fostering new forms of design agency.

In doing so, landscape architecture engages more deeply with the complex material and temporal realities of the Anthropocene, moving beyond metaphor toward metamorphosis, as Reggio describes. Computation becomes not merely a technical instrument but a conceptual and perceptual catalyst reshaping how landscapes are sensed, understood, and transformed.

As a contribution to digital landscape architecture, this work formalises a reproducible workflow for AI-assisted temporal resampling, demonstrating how emerging technologies expand the perceptual and cognitive horizons of the discipline, bridging data, image, and imagination in the design of dynamic environmental systems.

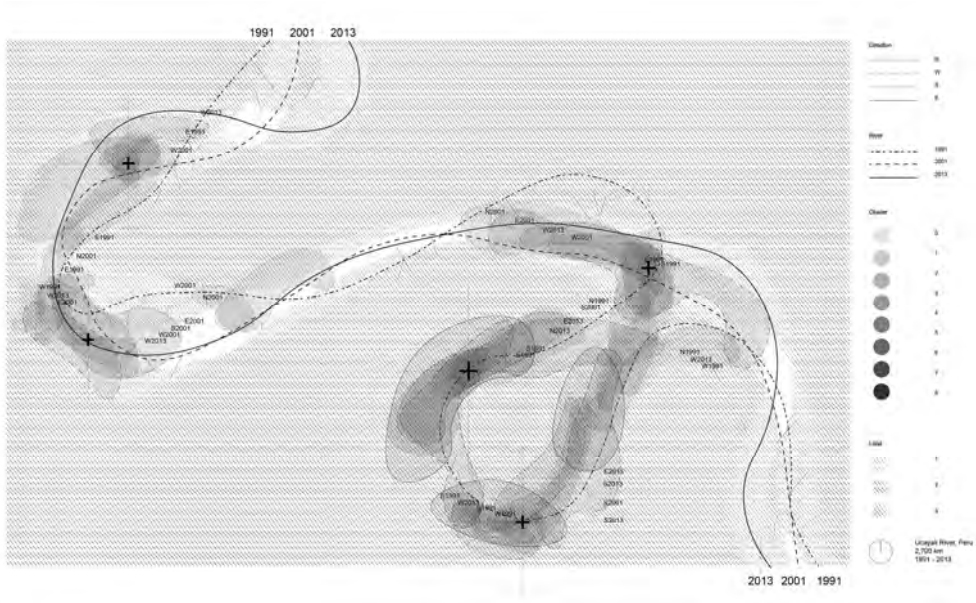

Fig. 7: “Temporal Intensities” by Emi Kim

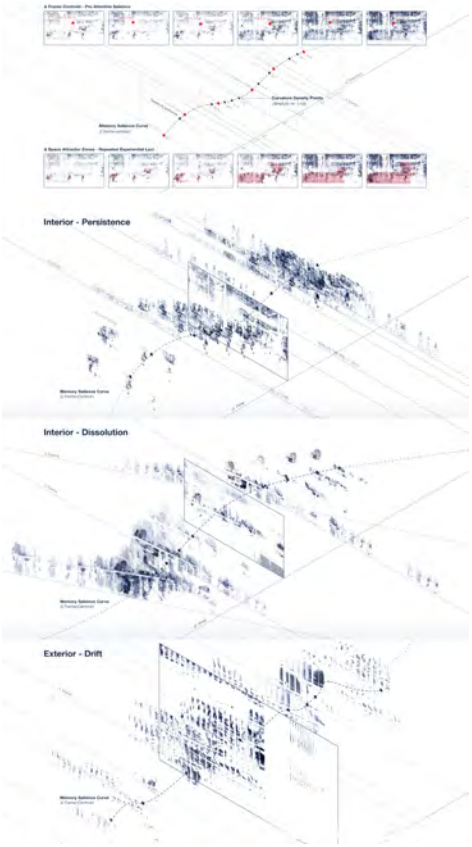

Fig. 8: "Afterimage Inscriptions" by Hannah Lin

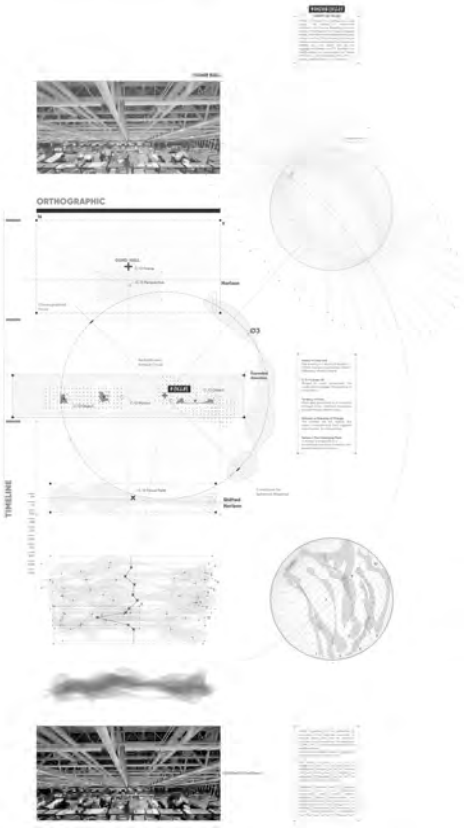

Fig. 9: "Focus: Verify" by Sanchit Agrawal project

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A Field-Ready Image-Based Method for Soil Texture Assessment in Urban Landscapes

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Abstract: This study explores a field-deployable soil texture classification method based on mobile images. Soil texture is one of the fundamental elements of a successful landscape project. It impacts plants' root growth, drainage, moisture balance, and the overall resilience of an ecosystem, making it a core metric of planting success, stormwater function, and long-term sustainability. Conventional texture analysis, however, relies on laboratory equipment and sampling procedures that are time-consuming and costly. This study explores a Soil Texture Recognition Platform (STRP) based on mobile phone images to quickly identify texture types on real soil surfaces without laboratory processing. It employs Convolutional Neural Network, texture feature extraction, and supervised learning model training. Through a comparison experiment based on manual and platform-based evaluation, the researcher assesses and further improves this STRP's effectiveness and accuracy. This research provides the landscape architecture field with a low-cost, reproducible, and rapid method for soil texture testing, contributing to evidence-based design and smart landscapes.

Keywords: Urban soil texture assessment, image-based analysis, machine learning, smart landscapes

1 Introduction

Soil texture is one of the primary factors that impacts plant survival, root development, water infiltration and retention, and long-term stability (BRADY & WEIL 2008). In urban settings, soil texture conditions decide irrigation efficiency, stormwater performance, soil compaction risk, and maintenance costs (CRAUL 1992, PHILLIPS et al. 2019). Although soil has significant ecological and engineering value in the field of landscape architecture, texture assessment has not become a routine step in actual design and management. Instead, many decisions rely on professional experience, rather than consistent and repeatable field-based data. On-site designers and researchers commonly use the Soil Texture-by-Feel Method (FRANZMEIER & OWENS 2008) and Soil Sedimentation Test (PALTSEVA 2024) to analyze soil texture. However, both methods have certain limitations. The soil texture-by-feel method is inherently subjective and requires training to achieve reliable results, and its accuracy can vary from one practitioner to another. Although these two methods can provide reasonably accurate results, they are labor-intensive, time-consuming, and impractical for large-scale or frequent field tests.

Urban soils are complex and heterogeneous, with soil composition varying substantially across different features, such as planting areas, lawns, pedestrian walkways, and stormwater facilities. These spatial differences affect plant growth, irrigation efficiency, and soil remediation priorities, necessitating more extensive and frequent on-site assessments to guide design and maintenance decisions (HERNANDEZ et al. 2017). Also, with growing interest in urban agriculture (HODGSON et al. 2011), the need for more detailed and spatially resolved urban soil information has increased accordingly. Historically, the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) did not tradition-

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ally map urban soils (OHM et. al. 2024), leaving significant knowledge gaps in densely developed areas. At the same time, a growing body of research and professional literature underscores the importance of urban soil practices (RAKSHIT et al. 2022, RATE, 2022), and the USDA has also addressed this topic through its Urban Soil Primer (SCHEYER & HIPPLE 2005).

On the one hand, there is a growing demand for high-resolution soil data covering large areas; on the other hand, such data is severely scarce, which is one of the greatest challenges (GRUNWALD et al. 2011). Obviously, the two methods commonly used by landscape architecture professionals, because of their labor demands and the disturbance caused to the site, make it difficult to obtain soil information at a meaningful spatial resolution or to update it on a regular basis. The landscape architecture field needs a rapid, low-cost, and reproducible method to support rapid on-site soil texture assessment. With advancements in imaging technologies, utilizing visual cues on the soil surface as indicators of texture characteristics has increasing potential. This study explores high spatial resolution soil texture analysis methods and tools based on mobile phone images that can be directly applied to the field for rapid estimation of soil texture in urban environments to support future urban landscape design and workflows. At the same time, it also contributes to making up for the lack of high spatial resolution soil data in urban environments.

2 Materials and Methods

Figure 1 illustrates the study's three main stages, including: 1) Building a Soil Texture Recognition Platform (STRP); 2) field soil sample collection and texture identification; 3) model retraining and evaluation.

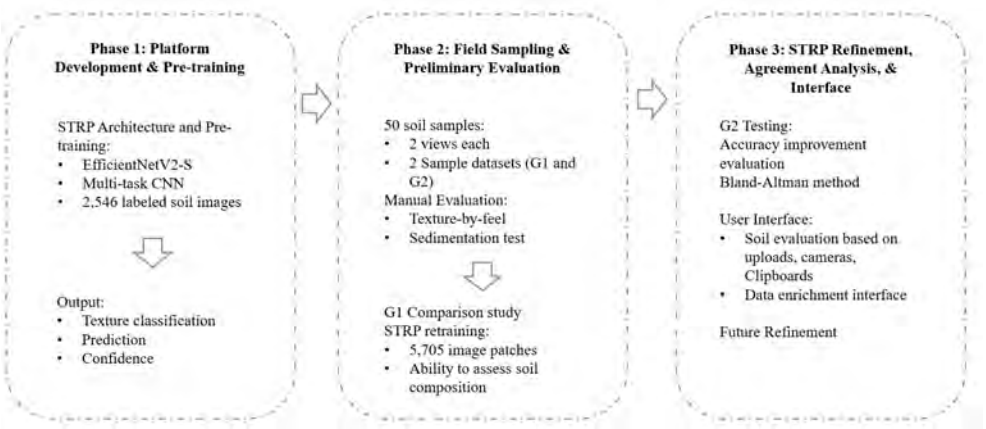

Fig. 1: Conceptual diagram of the research

This STRP is built upon a multi-task learning Convolutional Neural Network, which is specialized algorithms primarily used for image recognition. It can perform soil texture classification and particle composition prediction simultaneously. The employment of EfficientNetV2-S ensures the balance between accuracy and computational efficiency. Three main

components of this STRP include: 1) a feature extraction model that processes input images into high-dimensional feature representations, (2) a classification head that predicts soil texture classes, and (3) a regression head that predicts continuous percentages of sand, silt, and clay particles. This multi-task learning approach enables the model to leverage both categorical and compositional information during training, improving overall prediction accuracy.

The researcher first conducted the pre-training phase. The model was initially pre-trained on a curated dataset of 2, 546 soil texture images (852 clay, 859 loam, and 835 sand) to learn general features distinguishing different soil textures. This pre-training phase helps the model develop robust feature representations before fine-tuning on field-collected samples.

All images imported into the STRP are initially pre-processed to ensure a consistent image format. The image preprocessing workflow includes white balance correction using a detected reference card (or the gray-world assumption when a reference card is unavailable), contrast enhancement based on Contrast Limited Adaptive Histogram Equalization, resizing to a uniform resolution of 500 x 500 pixels, and normalization using ImageNet statistical parameters. Pre-training employed standard data augmentation techniques (random flips, rotations, color jittering, and cropping) to improve generalization and robustness to field variability.

The research team identified a total of 50 soil sampling points (Figure 2) on the University of Georgia campus and in surrounding areas based on four common urban soil scenarios: (1) tree lawns, (2) planting beds, (3) pedestrian sidewalk edges, and (4) retention ponds. Field data collections were conducted between September 15th and November 15th in 2025. This is the seasonal change and leaf drop period in the Atlanta-Athens metropolitan area with variable soil conditions. At each sampling point, the researcher gently cleaned the surface debris, such as leaves or mulch fragments, without disturbing the surface soil structure. The researcher used 4 field marking flags to create a 0.6m x 0.6m (2ft x 2ft) sampling boundary and puts a Tri-color reference card at one corner for the purpose of white balance correction. Two photos were taken by the smartphone: one top view (90°) of the site at approximately 2ft above the surface and one oblique photo (45°) about 3ft above the surface. A portable GPS was deployed to record the location.

Fig. 2:
Spatial distribution of the 50 soil sampling sites in the study area. The soil texture base map presented in the figure is based on data from the USDA Soil Survey Map (UNITED STATES DEPARTMENT OF AGRICULTURE (n. d.)).

These 50 soil samples were manually analyzed for soil texture using the Soil Texture-by-Feel Method and the Soil Sedimentation Test. This process served two purposes: (1) to conduct cross-comparative experiments for preliminary evaluation of the STRP's accuracy, and (2) to assign texture labels to the samples for inclusion in the STRP training process, thereby

improving its classification performance. Images of the 50 samples were divided into two groups (G1 and G2), 25 samples (50 images) each group.

The 50 images in G1 were first used to evaluate the accuracy of the STRP's predictions after pre-training through the comparison study based on the STRP outputs and manual assessments. After that, these images were processed through the platform's image processing pipeline, generating a total of 5,705 image patches with a resolution of 500 × 500 pixels. These images have soil texture labels and quantitative component proportions derived from the Soil Sedimentation Test. They were imported into the system to further train the STRP. This process not only improved the model's classification performance but also enabled the prediction of soil component proportions (sand, silt, and clay) from soil images. The remaining 50 images in G2 were reserved as an independent test set and used exclusively for the final evaluation of the STRP's predictive accuracy and generalization performance.

The STRP is implemented as a server-based web platform, providing an intuitive interface for soil texture analysis. This web interface provides two primary functions: 1) Rapid soil texture evaluation (Figure 3), which outputs texture classes with confidence scores, predicted percentages of texture components, and a visualization of the prediction on the soil texture triangle diagram; 2) Allowing users to upload soil images with verified texture labels to expand the dataset and increase training volume, thereby improving overall model performance.

Fig. 3: The user interface of the rapid soil texture evaluation function (left) and an example of the STRP outputs on the user interface (right)

3 Results

Table 1 presents an example of the STRP's analytical results for a soil image in G1 after the pre-training stage. All prediction results are originally stored as a single row in a CSV file; for clarity and readability, the result format in Table 1. has been manually reorganized. For each prediction, the system analyzes the input image and outputs the five most probable soil texture classes along with their corresponding confidence scores. The system ranks the predicted texture classes from the highest to the lowest probability (Top-1 to Top-5). The class with the highest confidence is selected as the final predicted texture and is reported to the user together with its associated confidence value. The top five predicted texture classes and

their confidence scores are reported to reflect the uncertainty present at this early stage of model development. This design allows users to view both the most probable prediction and several plausible alternatives. More importantly, it allows the researcher to obtain more informative details for evaluating the STRP's performance than a single deterministic label.

Table 1: Example of STRP analytical output after pre-training stage

Image Name	**Sample ID**	**Predicted Class (Top-1 Class)**	**Confidence (Top-1 Prob.)**
007_2.png	14	Sandy Loam	0.6851760745
Top-2 Class	**Top-3 Class**	**Top-4 Class**	**Top-5 Class**
Loamy Sand	Silt Loam	Loam	Sand
Top-2 Prob.	**Top-3 Prob.**	**Top-4 Prob.**	**Top-5 Prob.**
0.2066360861	0.03786857054	0.01919812523	0.0101066893

The validation results of the 50 images in G1 indicate that, after the pre-training stage, the STRP achieved a Top-1 classification accuracy of 78%, with 39 predictions matching the manual assessments. For the remaining 11 misclassified samples, the correct soil texture labels were consistently ranked as the Top-2 predictions. When considering the top two ranked predictions, the correct texture label was included in all cases. All errors occurred between sandy loam and its neighbouring texture classes. Specifically, six samples were misclassified as loam and five as loamy sand.

Regarding prediction confidence, the average confidence score across all 50 samples was approximately 0.60. For the 39 correctly classified images, the mean confidence was 0.62. In contrast, the 11 misclassified images exhibited a lower average confidence of 0.54 for the incorrect Top-1 predictions, while the confidence assigned to the true classes was notably lower, with a mean value of 0.26. The descriptive statistics of these confidence distributions are summarized in Table 2.

Following retraining with the 5,705 samples with corrected texture labels created from G1, the STRP was capable of producing extended outputs for each new soil image, including predicted percentages of sand, silt, and clay in addition to the information listed in Table 1. The testing results of the 50 samples in G2 using the refined STRP indicate that 44 images were correctly classified in terms of soil texture, while 6 were misclassified, resulting in an overall accuracy of 88%. Similarly, for the six misclassified samples, the correct texture labels consistently appeared as the second most probable class in the prediction outputs. Table 3 summarizes the prediction confidence of the refined STRP evaluated using the 50 images in G2. Compared with the initial testing results reported in Table 2, the refined STRP exhibited higher overall confidence in its predictions. In addition, the ratio between the standard deviation and the mean, the coefficient of variation, indicates that the stability of the STRP also improved, with the CV decreasing from 28.61% to 21.39%.

Table 2: Descriptive statistics of prediction confidence for samples in G1

N	Class Name	Minimum	Maximum	Mean	Std. Deviation
50	Predicted Class Confidence (Top-1 Class Prob.)	0.3178	0.9540	0.6036	0.1727
39	Predicted Class Confidence (Top-1 Class Prob.)	0.3178	0.9540	0.6211	0.1764
11	Predicted Class Confidence (Top-1 Prob.)	0.3830	0.8865	0.5416	0.1508
11	Top-2 Prob.	0.0584	0.3678	0.2628	0.1038

Table 3: Prediction confidence of the refined STRP evaluated on samples in G2

N	Class Name	Minimum	Maximum	Mean	Std. Deviation
50	Predicted Class Confidence (Top-1 Class Prob.)	0.5125	0.9737	0.7068	0.1512
44	Predicted Class Confidence (Top-1 Class Prob.)	0.5125	0.9737	0.7163	0.1310
6	Predicted Class Confidence (Top-1 Prob.)	0.4917	0.7538	0.6153	0.1424
6	Top-2 Prob.	0.1538	0.2367	0.1774	0.0833

As a pilot evaluation, agreement between the STRP-predicted soil component proportions and the sedimentation-based measurements was examined using Bland-Altman analysis (DOĞAN 2018). The objective was not to establish definitive quantitative equivalence, but to explore initial agreement patterns and identify systematic limitations. For sand and silt contents, the differences between the two methods showed moderate dispersion. According to the results of difference descriptive statistics (Table 4), the mean bias was +5.65% for sand and −2.49% for silt. Approximately 93% of the observations fell within the 95% Limits of Agreement (LoA). These results suggest a moderate level of agreement between the two methods at this preliminary stage (Figure 4). In contrast, the agreement for clay content was notably lower, characterized by larger dispersion of differences and wider limits of agreement. Although most clay observations were located within the 95% limits of agreement and the absolute differences appeared small, the relative errors were substantially larger due to the small magnitude of clay content. Thus, the overall agreement remained limited. This indicates that, compared with sand and silt, the current STRP still exhibits considerable uncertainty in predicting clay proportions.

Table 4: Descriptive statistics and agreement analysis of soil texture fractions

Soil Fraction	Method	Mean	Std. Deviation	Mean Bias	95% LoA	% within LoA
Sand	Manual	55.83	20.04	5.65	[-21.31, 32.61]	93.20%
	STRP	61.48	17.70			
Silt	Manual	39.77	20.61	-2.49	[-30.67, 25.68]	93.20%
	STRP	37.28	17.45			
Clay	Manual	4.40	2.45	-3.16	[-8.17, 1.85]	100%
	STRP	1.24	1.54			

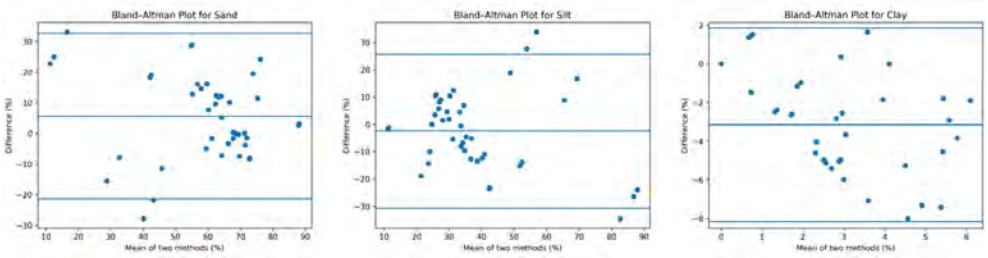

Fig. 4: Results of Bland-Altman analyses

In the web-based interface, users can upload soil images via local files, a camera, or the clipboard. After submission, the system generates the analytical outputs shown in Figure 3 within approximately 5 seconds. Users may also switch to an alternative interface to upload images together with manually annotated component proportions. These images are stored on the server and undergo both automated and manual validation before being incorporated into the STRP training dataset.

4 Discussion and Conclusion

This study explores a rapid, image-based soil texture recognition method, the STRP, and conducts a two-stage experimental evaluation of its performance in soil texture and composition prediction. The results indicate that the STRP is capable of providing soil texture information with practical reference value without requiring laboratory conditions, offering a new technical pathway to support rapid decision-making in urban landscape design and management.

At the soil texture classification level, the STRP achieved a Top-1 accuracy of 78% in the pre-training stage, which increased to 88% on the independent G2 test set after model refinement. In addition, across both experimental stages, the true soil texture class of every misclassified sample consistently appeared within the Top-2 prediction results. This finding suggests that although uncertainty remains when distinguishing between closely related texture classes, the STRP outputs are reliable at the candidate-range level. From an application per-

spective, this “Top-2 full coverage” characteristic is particularly valuable for field-based assessments, as it allows users to rapidly narrow down plausible texture categories under uncertain outdoor conditions.

Prediction confidence analysis further reveals changes in model performance over the training process. After retraining, the STRP exhibited a higher average confidence on the G2 dataset, accompanied by a clear reduction in the coefficient of variation. This indicates an improvement in output stability. These results suggest that incorporating field-collected data with manual verification into the retraining process not only enhances classification accuracy but also reduces prediction variability across samples, providing a foundation for further model improvement.

Bland-Altman analysis of agreement between STRP-predicted soil component proportions and sedimentation-based measurements indicates a moderate level of agreement under the current experimental conditions. This does not directly imply that the STRP can replace laboratory-based compositional analysis, but rather that it provides reference-level quantitative information at the scale of overall trends and magnitudes. Agreement was notably weaker for clay content. One possible explanation is that although the USDA soil survey map (Figure 2) suggests a certain proportion of clay within the study area, manual assessments revealed that most samples were dominated by sandy loam with very low clay content. In urban environments, soils are often disturbed by construction activities, grading, fill materials, and other engineering processes, which can substantially alter fine-particle distributions. As a result, the STRP may not have been sufficiently trained on clay-rich samples under field-representative conditions. This limitation also reflects the broader challenge of image-based feature representations in capturing fine-scale soil structure, particularly for clay fractions. Addressing this issue may require expanding the training dataset, incorporating multi-scale image features, or integrating complementary sensing information. In addition, the current field dataset is limited in both sample size and geographic coverage. Larger and more diverse datasets encompassing a wider range of soil textures will be necessary to improve the model’s ability to represent complex urban soil conditions. Future work may also explore integrating the STRP with GIS or digital twin platforms to support higher-resolution urban soil modeling.

Overall, this study contributes a new paradigm for landscape architecture by combining artificial intelligence with in-situ sensing approaches. The current STRP demonstrates the ability to extract meaningful soil texture and compositional information from complex urban environments with a reasonable level of accuracy and stability. It shows potential to support research relates to urban soil diagnosis, stormwater management, planting design, and irrigation planning. As a pilot study, the objective of this research is not to achieve perfect agreement with high-precision laboratory measurements, but rather to demonstrate the feasibility and practical value of a high-frequency, low-cost, non-destructive, and scalable approach. Thus, another primary contribution is exploring the applicability and limitations of image-driven methods for urban soil assessment.

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Capacity Building: A Bibliometric Study on Research in [Digital] Landscape Architecture

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Abstract: Research in landscape architecture is expanding, but many contributions come from related fields rather than trained landscape architects. This paper investigates which disciplines contribute to landscape architecture knowledge and its implications for the profession. Using bibliographic data and scientometric analyses, it traces publication trends since the 1990s, highlighting the field's growing scientific nature, its coevolution with engineering and the environmental sciences, and its focus on issues such as climate change. The paper encourages landscape architects to assert their expertise and support emerging scholars.

Keywords: Capacity building, knowledge dissemination, landscape architecture, digital technologies, bibliometrics

1 Introduction

Since the 1990s, scholarly publications in landscape architecture have increased more than tenfold (see Figure 1). Although the field was traditionally practice-oriented, emphasizing creative and aesthetic work over research and theory (CUSHING & RENATA 2015), academic institutions now see scholarly publishing as vital for career advancement, as it showcases research activity and knowledge sharing. The field created its own platforms for publishing design research in landscape architecture and welcomed contributions from students and practitioners (GILL & RINALDI 2022). However, rising editorial standards during the 2000s made it harder for non-academics to meet strict requirements and justify the time spent on writing (VICENZOTTI et al. 2016). Furthermore, professional training in landscape architecture does not adequately prepare scholars (PATERSON 1995), thereby creating a gap between theory and practice. In their 2010 survey, GOBSTER et al. (2010) found that only 6% of landscape architecture faculty in North America published peer-reviewed papers annually, with nearly half having not published in the previous decade. Despite this, there is a significant need; studies find that fewer than 10% of landscape architects believe that sufficient research is being conducted in the discipline (CUSHING & RENATA 2015). Consequently, much of the emerging knowledge stems from related fields (see Figure 1), raising questions about who is generating the knowledge base within landscape architecture.

Landscape architecture must expand its knowledge base to support academic growth, as ZUBE (1998) suggested. GOBSTER et al. (2010) note this involves addressing practice-related topics aligned with values and fostering scholarship through collaborations. Barriers include a lack of discipline-specific research protocols and difficulty integrating research into broader frameworks (SWAFFIELD & DEMING 2011). Additionally, funding is limited due to undefined research problems and weak peer review (THWAITES 1998). With shifts toward evidence-based practice (BROWN & CORRY 2011) and digital tech like AI (FERNBERG & CHAMBERLAIN 2023), have scholars overcome publishing barriers?

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Using quantitative analysis from the fields of bibliometrics and scientometrics, this study highlights key research topics shaping landscape architecture from 1990 to 2025. Our objective is to situate landscape architecture scholarship across all disciplines and assess "where" landscape knowledge is most prevalent, with the hope of identifying "cutting-edge" trends.

2 Methodology

We carried out the research in three phases: data collection, disciplinary analysis, and co-occurrence analysis. We collected the data through an initial bibliometric analysis of leading scholarly sources on the Web of Science platform. Bibliometrics uses published scientific literature (articles, books, and conference proceedings) to measure scientific activity. The core idea is that new scientific knowledge is embedded in documents and metadata (titles, abstracts, affiliations, references, etc.), and by analyzing these, we can measure the knowledge produced by a field (LARIVIÈRE & SUGIMOTO 2018). Articles and books are peer-reviewed by a scientific community (MERTON 1973) and ensure that the information has reached a certain level of validity (KELLY et al. 2014). Additionally, the literature is indexed and accessible. Managed by Clarivate Analytics, the Web of Science comprises over 21,000 high-impact journals spanning STEM, the social sciences, and the humanities. It is a curated, selective database that tracks citations received by articles and aggregates those in the Journal Impact Factor, a well-known indicator used to rank scholarly journals. Bibliometric databases such as the Web of Science use a journal-based disciplinary classification that assigns journals to a single discipline. Those typologies are relatively conservative and generally do not have new areas, such as landscape architecture, in their classification, which is why we relied on a mix of keywords and specific journals to define the discipline.

Given the current article's position in the *Journal of Digital Landscape Architecture*, we selected the five subject areas listed on the journal's website: Landscape architecture, Landscape planning, Landscape modelling, Landscape visualization, and Landscape analysis. However, an initial search yielded over 200,000 articles, and reviewing the abstracts suggested that the term "landscape" is used across many disciplines without being specific enough to "landscape architecture." To improve relevance, we adjusted the search terms to ("land*" and "arch*"), ("land*" and "plan*"), ("land*" and "model*"), ("land*" and "visual*"), and ("land*" and "analy*"). Our refined search includes 23,757 articles published between 1991 and January 7, 2026. We extracted metadata from those papers (titles, abstracts, authors, affiliations, journals, and disciplines, among others) to create a database for analysis.

3 Results

3.1 Discipline Results

Based on our bibliometric study, the number of scholarly papers in landscape architecture has exploded from approximately 100 per year in the 1980s to over 7,000 in 2025. The top six producing countries are China, the United States, England, Italy, Germany, and Canada. In addition to individual scholars and academic institutions, national forestry, agricultural, and environmental research agencies are named as contributors. The most cited discipline is

ecology, followed by physical geography and environmental studies, with urban studies next. Funding supports these results: the top six funding agencies are the National Natural Science Foundation of China, the Instituto Politécnico Nacional (Mexico), the National Science Foundation, the European Union, the United States Department of Agriculture, and the UK Research Innovation.

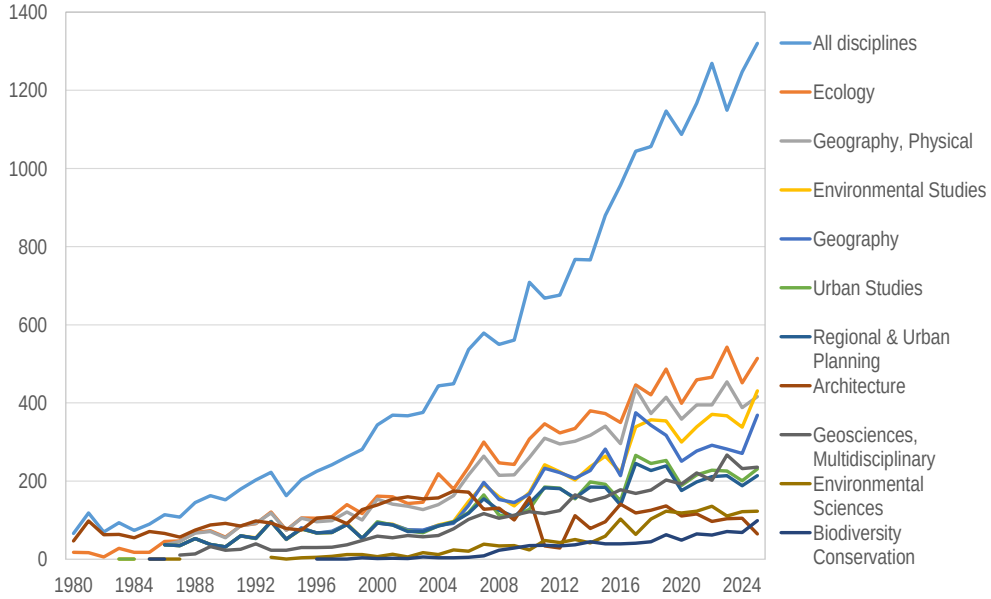

Fig. 1: Annual number of in landscape architecture-related scholarship, by discipline and all disciplines combined (Authors, 2026)

Figure 1 shows that landscape scholarship has increasingly appeared in disciplines beyond architecture and ecology since the 1980s. The growth began in urban studies and the geosciences, then expanded to biodiversity, conservation, environmental science, and, by the end of the decade, to regional planning and physical geography. Leading up to the millennium, scholarship spread to environmental studies and geography more broadly. In the early years, well over half of all scholarship was published in architecture journals, whereas today less than 20% is. Meanwhile, 42% appears in ecology publications. Computer and digital sciences do not appear.

3.2 Co-occurrence Results

Disciplinary co-occurrence involves examining how different academic fields, subjects, or topics appear together in research, education, or professional practice. It helps reveal connections and structural relationships within knowledge domains. Typically, network visualizations highlight interdisciplinary trends, such as collaborations between biologists and visual artists. This concept builds on network analysis and text mining, extending the idea of word co-occurrence – where words are found together in titles or abstracts – to broader academic areas (LARIVIÈRE & SUGIMOTO 2018). It enables mapping interdisciplinary relationships and identifying emerging research areas.

Figure 2 shows 108 academic fields or subjects as network nodes, arranged by proximity in our set of landscape architecture papers. Lines connecting each pair of nodes indicate that there are articles belonging to both disciplines simultaneously, and thus, those disciplines are considered related. The size of each circular node reflects its degree – in this context, the co-occurrence frequency of disciplines – with the smallest circle representing five co-ocurrencies and the largest representing 50. The colour of each node, ranging from dark purple to light green, represents betweenness centrality, highlighting how frequently a discipline appears on the shortest path between other disciplines.

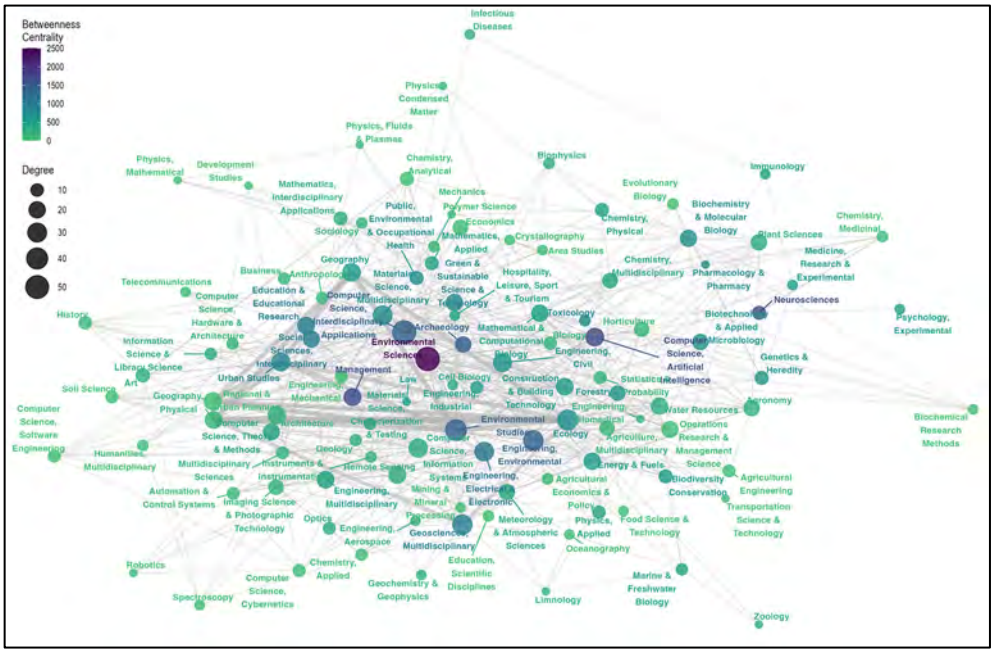

Fig. 2: Network of the relationship between disciplines of journals that published landscape architecture papers, Authors, 2026. Node size expresses degree centrality (how well-connected a node is to other nodes), and the colour gradient expresses betweenness centrality (how often a node lies on the shortest path between other nodes). Only nodes with a degree of at least 5 are shown in the figure.

The diagram does not explicitly name landscape architecture as it is not a field in itself in the database; instead, it produces a robust triangulation around approximately twenty central fields or subjects associated with journals that published landscape architecture papers. Geography sits at the apex of the triangle, Ecology at the bottom-right, and two points form at the bottom-left corner – namely, Regional and Urban Planning and Physical Geography. The pathway from Geography to Regional and Urban Planning traverses through Anthropology, Education and Educational Research, Interdisciplinary Studies, Social Sciences, and Urban Studies, before reaching Ecology via Archaeology and Civil Engineering. The boundary along the lower side of the triangle intersects with Environmental Studies, Architecture, and Computer Science, Theory & Methods. An internal, secondary triangle is also present, con

necting Multidisciplinary, Interdisciplinary Applications, and Environmental Sciences. The Environmental Sciences node has the deepest colour and is one of the largest. Computer Science and Interdisciplinary Application is the only obvious digital technology within the triangle, on one of the dominant lines.

Outside the triangle, we find additional connections between landscape architecture and digital topics: Computer Science, software, and engineering; Computer Science, hardware, and architecture; Computer Science and Cybernetics; Computer Science and Artificial Intelligence; Computer Science, theory and methods; and Computer Science and Information Science. We also find Remote Sensing, Imaging Science and Photographic Technology outside the triangle.

3.3 Topics Results

Using the BERTopic algorithm (GROOTENDORST 2022), Figure 3 presents the topic space obtained from the Web of Science research articles containing our five subject key terms.

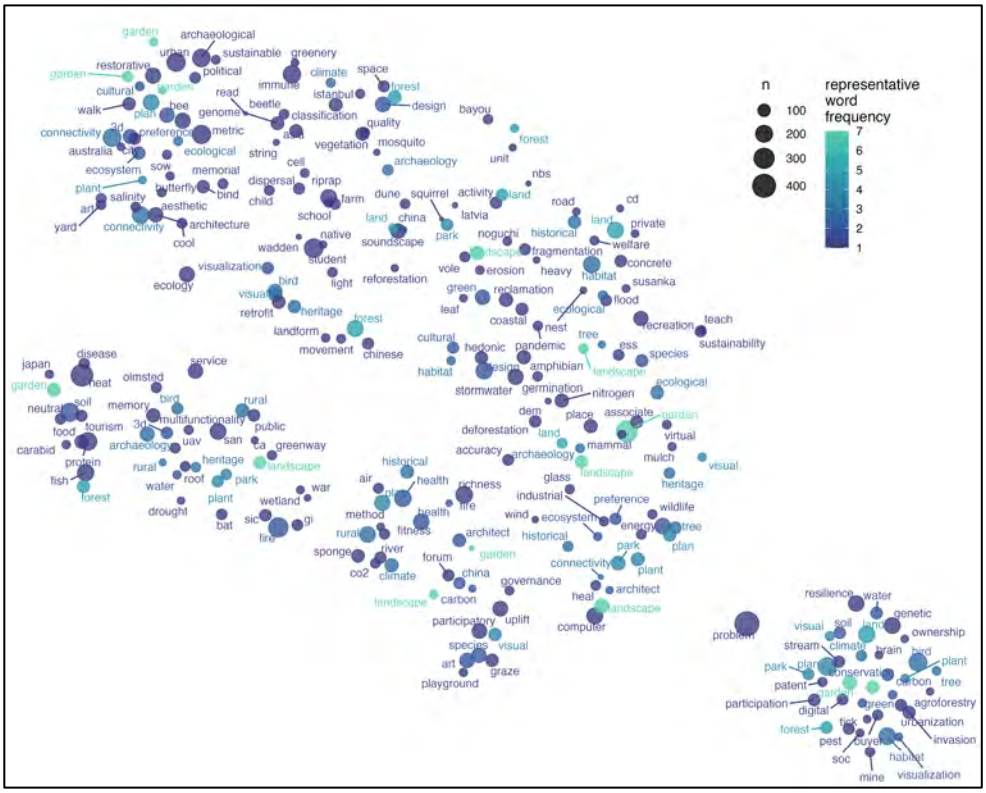

Fig. 3: Scholarly topics published in Landscape Architecture from 1991 to January 2026, Authors, 2026. The figure is a 2-dimensional representation of the semantic space occupied by research papers, with the most representative word for each topic as a label. Size represents the number of documents in each topic, and colour shows the relative frequency (or specificity) of the most representative word within each topic.

This visual representation systematically arranges these topics by their proximity to related subjects in or about landscape architecture. The lighter colours represent the subjects most closely related to landscape architecture, and the darker a topic's colour, the rarer its representative terms, suggesting greater overlap with other disciplines. The closeness of the dots indicates a high semantic similarity between topics, suggesting related research questions. This diagram, akin to a word cloud, offers an insightful, visually appealing representation of current themes in landscape architecture and their relationships.

The light green dots symbolize themes considered fully within the domain of landscape architecture, as their most representative terms are the most frequent within our corpus (for instance, "gardens" and "landscapes"). The light green-blue dots, which include keywords like "forest," "land," "park," "plant," "climate," and "habitat," suggest an ecological orientation at different scales. The blue dots are less landscape architecture-specific and point to the interdisciplinary nature of the topics studied. On the whole, the maps show a distinct cluster at the bottom right, focused on climate change, as well as two other large, interrelated clusters, suggesting that the topics studied in landscape architecture are highly interconnected.

4 Discussion

The dichotomy between art and science in landscape architecture is often taught in professional programs and is clearly evident across a broad range of landscape architects' work. However, analysis of scholarly publications in the Web of Science suggests that research in landscape architecture is more akin to a natural science than to a creative field. We expected this finding, in part because the data are from high-impact scientific journal articles. However, SAUVÉ et al. (2022) reached a similar conclusion in their study of architecture, noting that engineering methods and materials have dominated architectural scholarship in recent decades. The study concluded that as architecture becomes a more scholarly pursuit, it becomes more global and technological. In part, Sauvé et al. argue that English has emerged as the dominant language for discourse and that the literature emphasizes academic perspectives over practical knowledge.

Indeed, English is the most common language for disseminating scholarship in landscape architecture. However, the topic diagram includes an – albeit small – range of country names (Australia, China, Japan, Latvia) and cities (Istanbul), indicating that impactful research is taking place outside Europe and North America. Moreover, it names a wide range of landscape typologies, including "rural," "park," "garden," and "forest," suggesting that the studies are more place-based than the apparent globalization of architecture scholarship would suggest. As for the technical aspects of landscape architecture, Figure 2 shows that technologies lie outside the triangulation and are being adopted in the field, but with less impact than in other disciplines.

Conversely, our findings indicate that landscape architecture possesses the capacity to influence numerous related disciplines, such as ecology through forestry, as well as immunology and infectious disease research, all of which are observable at the uppermost periphery of the discipline co-occurrence diagram (Figure 2). Although it is not entirely unexpected that landscape architecture is referenced in neurology and physics articles, it was somewhat surprising to observe the limited number of articles related to "digital" and interconnected disciplines.

Part of this expectation stemmed from the 2016 launch of the *Journal of Digital Landscape Architecture*, which facilitates knowledge dissemination and is available under an open-access license. However, a search for the term "digital" reveals that approximately 800 papers (0.03%) address this subject. Nonetheless, the journal remains relatively new and lacks sufficient citations to be indexed in the Web of Science.

5 Conclusion and Outlook

Scholarship plays a vital role in shaping and developing a discipline. Without it, landscape architects lack a documented record of what is effective, leading to repeated mistakes "with remarkable and embarrassing efficiency" (BROWN & CORRY 2011). Nevertheless, must all landscape architecture scholarship originate from landscape architects? Not necessarily. We can generate knowledge through interdisciplinary teamwork, which we are trained to do. Furthermore, we write in teams, as in many other fields, to increase our impact. The literature calls for us to take responsibility for our knowledge base to be more influential (ZUBE 1998, GOBSTER et al. 2010) and encourages cross-referencing multiple studies, expanding our scholarly reach and citation potential.

For now, finding the "cutting-edge" research topics in landscape architecture means being an attentive member of a professional association and learning by trial and error (BRAIDEN et al. 2025). While beyond the scope of our study, to get a complete picture of what is "current," we would need to study course syllabi (GAZVODA 2002) and built works (BROWN & CORRY 2011), as well as include books and document types beyond journal articles.

Bachelor's or master's degrees are terminal professional credentials. To emphasize research, we could advocate for more PhD programs in our discipline. If these degrees are valued, they would foster greater research engagement. Alternatively, we can create more research exposure within professional programs, including grant writing, which is vital since early-career researchers without a PhD face challenges accessing funding. Federal agencies fund established researchers, often those with prior grants, investing billions in medium- to large-scale projects. Not-for-profit "seed" funding is crucial for junior researchers to access larger funding pools later (BRAIDEN & LARIVIÈRE 2025).

An additional "capacity-building" challenge is the limited availability of landscape architecture-specific publications and their low publication frequency. For example, the *Journal of Landscape Architecture* and *Landscape Research* have collectively published fewer than 1,000 articles since their inception. Meanwhile, *Landscape Architecture Magazine* is a well-known source of landscape architecture content but features articles that are not peer-reviewed, along with letters and creative works. Future efforts could focus on enhancing scholarly publishing, encouraging training and investment in PhD programs, and creating a comprehensive list of influential articles and books to support emerging scholars.

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Public Life Study Datascapes that Visualize Space and Time

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Abstract: Public Life Studies (PLS) are widely used to evaluate public space, yet findings are often communicated through charts that flatten spatial and temporal nuance. This methods paper presents a hybrid workflow – community-based analog activity mapping, manual digitization, and algorithmic analysis/visualization – to generate "PLS datascapes". Using two temporary public space installations as case studies, we demonstrate how these visualizations reveal fine-grained spatial patterns and time-based behaviours that would remain hidden in conventional outputs, supporting more targeted design iteration and public communication of the social performance of public spaces.

Keywords: Public Life Study, data visualization, algorithmic analysis, social infrastructure, community-engaged scholarship, plazaPOPS

1 Introduction

This paper examines the use of community-based analog data collection methods, followed by data digitization and algorithmic computational tools, to create a type of visualization of Public Life Study (PLS) data that landscape architects can use to better evaluate the social performance of their designs. Going beyond standard PLS data visualizations, which typically result in pie or bar charts that communicate broad patterns and before and after comparisons about *who* was observed using a site, *what* people were observed doing, and *how* people were observed inhabiting a site, we outline a hybrid analog to digital method that results in the representation and analysis of PLS data that incorporates spatial and temporal dimensions. Allowing for a richer understanding of the public life occurring at a given site, and the impacts of a design or planning intervention, this method has the potential to enhance the design and evaluation of public spaces intended to function as social infrastructure.

The paper begins by discussing the typical outputs of the PLS method in research and practice. Next, based on research conducted to evaluate the social impacts of a temporary public space project designed by the authors, we outline the sequence of analog, digital, and computational methods we used for data collection, data digitization, data analysis, and data visualization, and showcase example datascape outputs. We discuss example spatial patterns that were revealed through this method, and to conclude, we reflect on the potential(s) of this method, and this type of visualization to communicate the spatial and temporal aspects of PLS data in an engaging and impactful manner.

2 Public Life Studies in Research and Practice

Environmental design evaluation (EDE) describes a broad research stream within landscape architecture and urban design concerned with the relationship between human experience and the designed environment, with intellectual roots that draw on multiple disciplines and

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date back to at least the early 1960s. EDE's origins were formed in response to the modern, vehicle centric, technocratic and top down design of post war urban renewal, by critics, scholars, and practitioners who built a foundation of critiques (JACOBS 1961), theories (LYNCH 1960, GOFFMAN 1963, SOMMER 1969, FRIEDMANN et al. 1978), and methods (GEHL 1971,WHYTE 1980, APPLEYARD 1980, JACOBS 1985, BOSSELMANN 2008). International research associations such as the Environmental Design Research Association (EDRA) and the International Association of People Environment Studies (IAPS), established in 1968 and 1981 respectively, have provided a forum for the formalization, testing and dissemination of EDE methodologies for decades.

Situated within the broader EDE tradition and building in particular on the work of William H. Whyte and Jan Gehl, the Public Life Study is a methodology focussed on measuring observable social life within the public realm, often comparing effects before and after an intervention. Depending on the objectives of the study, and the resources available, a typical PLS study can involve intercept surveys, mapping of the stationary behaviour of users of a site (activity mapping), and pedestrian and cycling counts. Importantly, the study is typically conducted prior to an intervention, and then during an intervention, so that changes in patterns of use can be quantified. A user-friendly overview of these methods was published in the book 'How to Study Public Life' (GEHL & VARRE 2013).

Activity Mapping within the PLS tradition is still primarily conducted using analog data collection methods, with researchers observing a site with a clipboard and filling out worksheets with a pen or pencil. While EDE pioneers like William H. Whyte captured video footage of public space, and today, novel and money saving techniques that utilize video camera footage and object detection and tracking algorithms are being experimented with (DHANESWARA 2020, SCHLICKMAN & DOMLESKY 2019), these approaches remain challenging to implement, at least in academic research overseen by human subjects research boards, due to ethical and perception concerns associated with this type of surveillance.

The mapping aspects of Public Life Studies are a powerful tool to systematically understand who is using a space (researchers record the perceived age and gender presentation of users), what users are doing (activities like eating, phone time, or socializing, for example) and the location and posture of the user (users are ascribed a dot on a map, and whether they are sitting, standing, leaning, or lying down is recorded). And, when studies are done 'pre' and 'during' an intervention, changes in user patterns can be quantified. A PLS can be an important quantitative tool to evaluate whether an intervention achieves certain project goals. For example, if a project has a goal to create a more welcoming and inclusive environment, Activity Mapping can determine whether the age and gender diversity of users increased as a result of the intervention, or not.

Many PLS studies tend to present findings in the form of statistical charts and tables (KIM 2016, PUBLIC WORK et al. 2018), measuring and evaluating overall patterns of use, but not delving deeply into analyzing these patterns through a more granular spatial lens. The results might include pie charts showing the age mix of users of the site at different hours of the day and could also find interesting statistical patterns about how the prevalence of activities may vary by gender and age, but most PLS studies do not explore the spatial dimensions of these patterns. Are there particular areas or elements of a site that also correlate with these observed use patterns, and, building on Randy Hester's ideas about 'enabling form' how can these findings add to a more a specific evaluation of how specific design features and qualities of the site might play a role in *enabling* certain behaviours (HESTER 2006)?

Exceptions exist, including findings presented in the SWA published 'Field Guide to Life in Urban Plazas: A Study in New York City' (SCHLICKMAN & DOMLESKY 2019), which named and illustrated 25 patterns of human spatial behaviour (postures, physical arrangements of people based on social activities) in response to the physical characteristics of the sites that were being studied. In general, though, this level of spatial analysis remains uncommon in the PLS literature, suggesting opportunities for further development of these methods.

Additionally, data related to the dimension of time is limited in typical PLS studies. Activity Mapping usually involves collecting data by the hour and on specified study days (often a combination of weekday and weekend days). Data can therefore be analyzed according to time of day, leading for instance to an understanding of the hours of the day when a site is busiest, and comparisons across the days of the week. Activity Mapping, however, does not typically capture more detailed information about the duration of time spent at a site by each individual person observed, allowing for a more nuanced understanding of temporal patterns, and analysis against spatial, demographic, and activity-based variables.

3 Methods: From Analog to Digital

This paper focuses on the Activity Mapping component of a PLS conducted in association with two temporary tactical urbanism installations in Toronto, Canada led by the authors, one installed during the summer of 2023, and one during the summer of 2024. Both installations were part of plazaPOPS, a multi-year public space design and research initiative, and located in the same neighbourhood, but at different sites about 300 metres apart. For both installations, field work took place *without* the installation, ie: when the installation was not present, to gather baseline data, and *with* the installation, ie: when the installation was present, to compare impacts to the baseline condition.

In total, there were four data collection periods (two for each installation), and attempts were made to keep the *with* and *without* study periods as comparable as possible, including ensuring comfortable temperatures and weather conditions, and that school was in session (ie. avoiding summer holidays). For each period, data was collected on four days (2 weekdays and 2 weekend days), for 14 hours each day. A total of 25 researchers were involved in the data collection, 14 in 2023 and 11 in 2024, a combination of Community Based Researchers (CBRs), and Graduate Student Researchers (GSRs) from the MLA program at the University of Guelph.

During each hour, researchers would observe the study area and fill out a worksheet on a clipboard that included a map of the study area, and an associated matrix (see figures 1 and 2). For each person who was stationary within the study area (ie: spending any amount of time in a stationary position, and not simply walking by), the researcher would draw a dot on the map, marking their spatial location, and ascribe the dot a number. On the corresponding matrix, information would be captured in a row with a matching number, including the perceived age and gender of the person, their posture and activity, whether they were part of a group, and the time that they started and stopped their stationary activity.

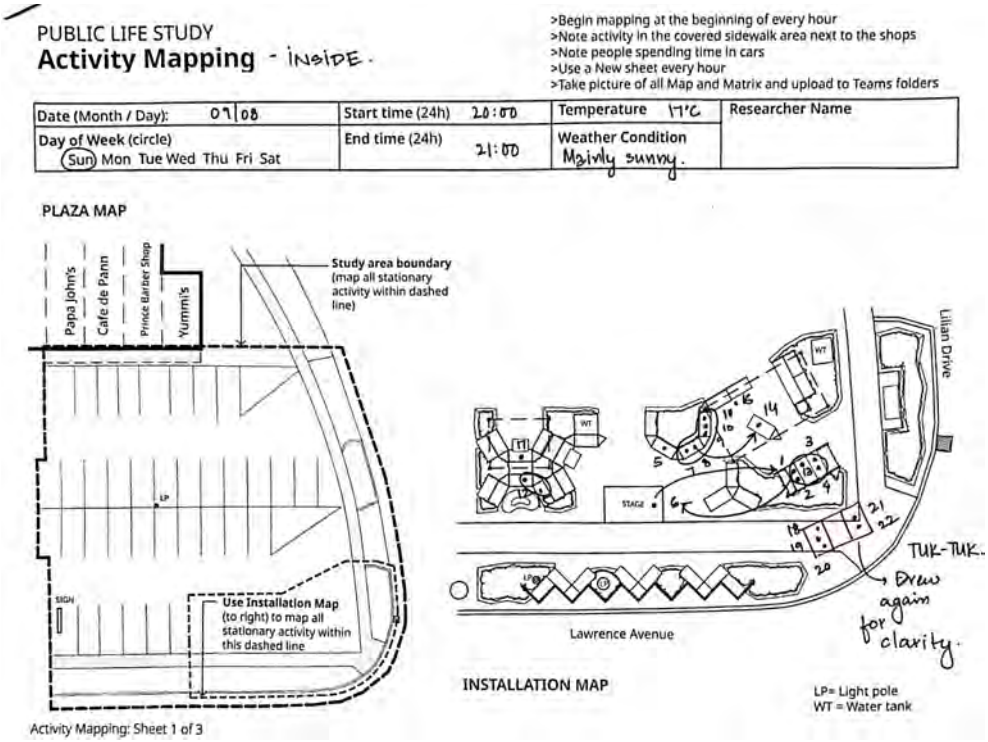

Fig. 1: Sample Activity Mapping map worksheet

All of the hard copy maps and matrices were collected and scanned, and then manually digitized into a master spreadsheet. The spatial location of each dot was entered as a latitudinal and longitudinal coordinate.

With the digitized data, Python libraries within Grasshopper, NumPy (numerical computing), Pandas (tabular data), and Matplotlib (2D plotting), were used to implement algorithms that generated pie charts and columnar summaries. Grasshopper components were then used to visualize and classify colors and exported into Adobe Illustrator to produce data visualizations.

Following data cleaning and restructuring, the finalized spreadsheet was directly linked to Grasshopper, enabling dynamic recognition and selection of multiple data attributes. Additional columns were generated during the preprocessing stage to aggregate category counts required for visualization, ensuring compatibility with specific chart types. Within Grasshopper, data were filtered and extracted according to the requirements of each visualization, allowing selected attributes and their corresponding quantities to be isolated and displayed using predefined color mappings. This workflow supported flexible, parameter-driven visualization while maintaining consistency across outputs.

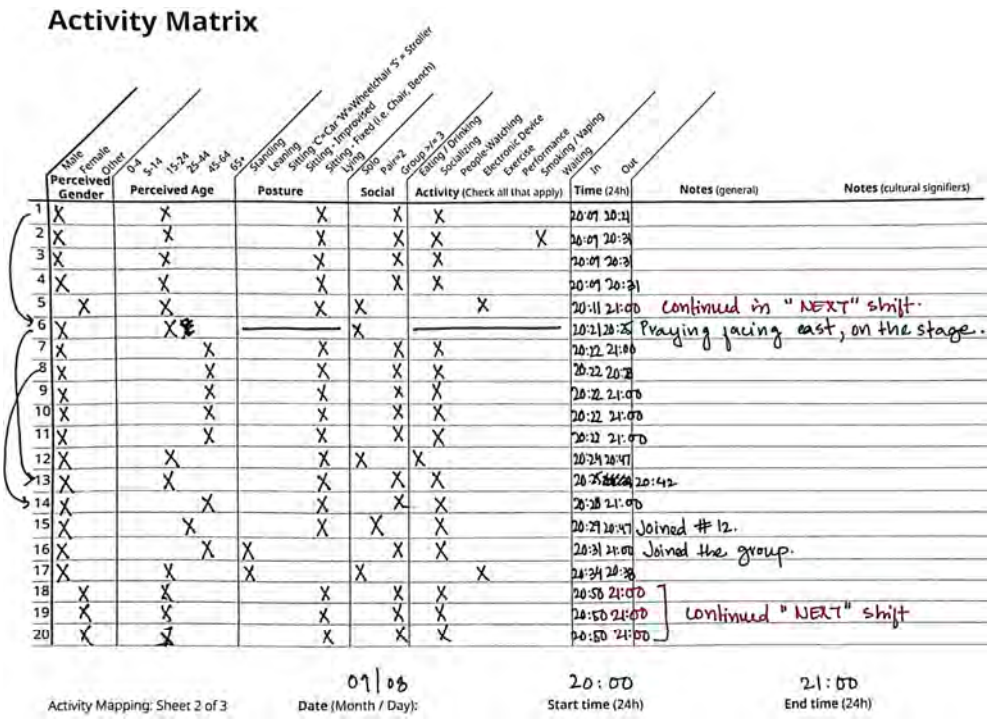

Fig. 2: Sample Activity Mapping matrix worksheet

In addition, Python scripting was used to analyze and visualize the distribution of selected parameters across three spatial conditions: *without* installation, *with* installation (inside installation), and *with* installation (adjacent to installation). For each condition, relative frequencies were calculated and normalized as percentages. These results were presented as side-by-side pie charts to facilitate direct visual comparison between conditions. Consistent formatting, color schemes, and percentage annotations were applied to enhance clarity and interpretability, enabling a comparative assessment of how selected parameters varied across installation scenarios.

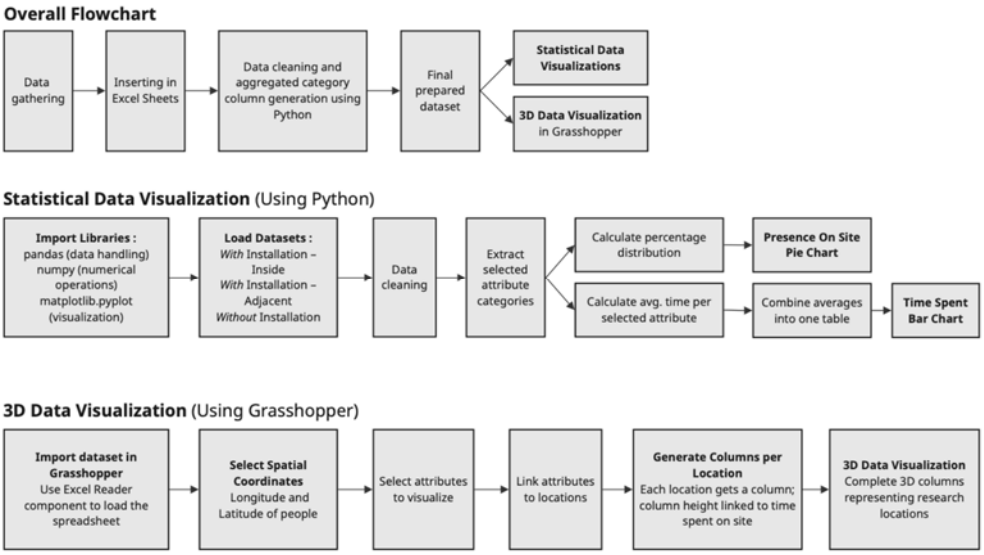

Fig. 3: Data analysis and visualization flow charts

4 Results – Spatial and Temporal Patterns of Public Life

To visualize the findings, datascape posters were created for each of five variables – *Age*, *Gender*, *Activities*, *Social Group* and *Posture* (figure 4 shows the Age poster for the 2023 site). The left half of each poster shows findings *without* the installation, and the right side shows findings *with* the installation. Colour schemes are consistent for each variable (pale yellow is the background colour for the *Age* variable), and associated categories use consistent colours (ie: green's and blues for each of the age ranges). These posters were exhibited at the Urbanspace Gallery in Toronto from September to December 2025, as part of *plazaPOPS: Paradise in a Parking Lot*, and will also be published in a public facing research report about the plazaPOPS initiative in 2026.

Each poster features "presence on site" pie charts that show the proportion of each category within each variable, ie: the Age poster for the 2023 installation (figure 4), includes charts showing that visitors in the 15-24 age range represented 11% of all observed people in the "without" condition, but grew to 32% of all people observed within the installation itself, in the "with" condition.

Each poster also includes "time spent" bar charts, illustrating the average amount of time (in minutes) that a person spent within the study area, organized by category. For example, on figure 4, the average 15-24-year-old spent 8 minutes at the site in the "without" condition, but 21 minutes inside the installation itself, in the "with" condition.

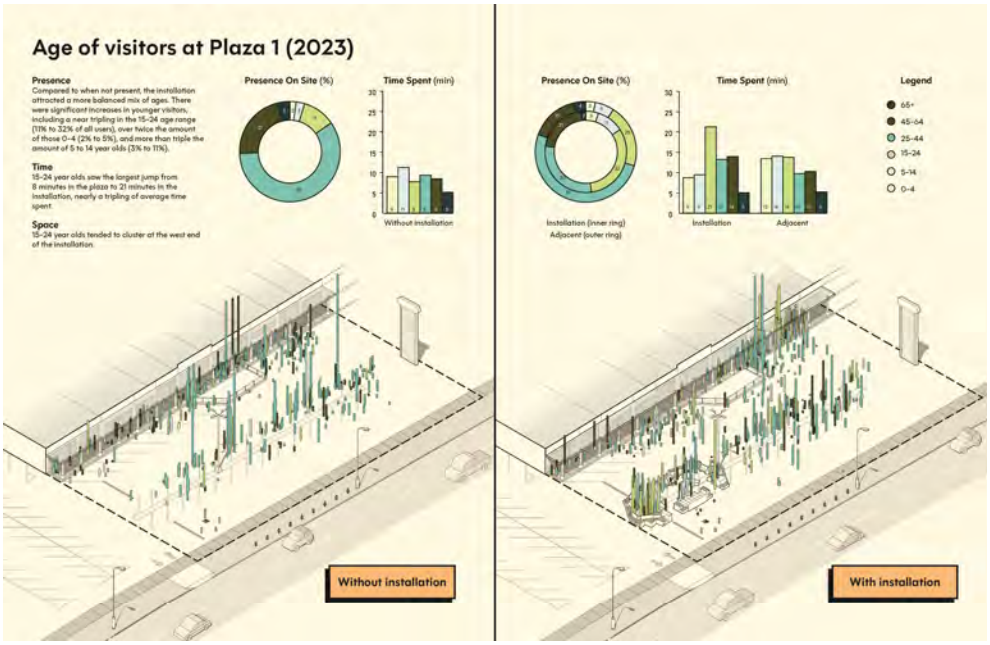

Fig. 4: "Age" Datascape for 2023 Installation

To complement and add depth to this statistical information, each poster features two axonometric maps of the study site. Individual people are represented as a column, colour coded based on the variables and categories, matching the pie and bar charts. The height of each column represents the duration of time spent, allowing for a quick visual understanding of patterns of use according to how much time people spent at the site, as well as broader spatial patterns.

In general, the study found that the installations led to more people being present at the sites, people spending more time, more gender balance, more age diversity, and more social behaviours. While this paper does not offer the opportunity for an in-depth discussion of all of the results, we offer an example of one significant spatial pattern that was revealed in the datascapes resulting from this method. The Age, Gender and Activities posters that analyze data from the 2024 installation revealed that in the "without" condition, middle aged men (aged 45-64) were found to socialize in the evenings, clustered in the shade of an existing sign on site. In the "with" condition, the pattern continued, but in a less spatially isolated manner; middle aged men continued to cluster in the same location, west of the installation site, but users of this age group were also distributed throughout the installation, amongst users of other age groups, suggesting that this group felt welcome within the installation, and perhaps even spent time interacting with groups of other ages.

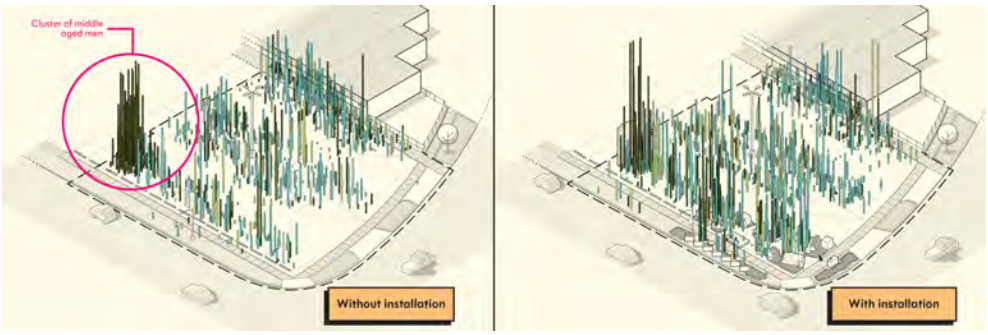

Fig. 5: "Age" Datascape for 2024 Installation, revealing spatial pattern of middle-aged men

5 Discussion

The data visualization method described in this paper has two key limitations. First, capturing the time in and time out for every user proved challenging during busy times on site, especially for the 2024 site, which was significantly busier than the 2023 site in all conditions. To mitigate this challenge, efforts were made as part of the "with" period of the study, to schedule an extra field researcher per shift during times of day that were known to be busier (typically evenings). One researcher focussed on use within the installation itself, while the other focussed on the remainder of the study area of the site adjacent to the installation. This approach proved effective, but was costly, and there still were times when the study area was so busy that time in and time out data was not captured or was incomplete. Incomplete lines of data were removed from the analysis, as a result.

This challenge was anticipated during the research design phase but capturing time in and time out for each site visitor was pursued regardless, to better understand whether capturing the duration of time spent would be possible, and whether the resulting analysis would reveal significant findings. This limitation represents a trade-off between quality and quantity of data captured and may only be appropriate on sites where activity levels are low enough to capture data with confidence, and/or where resources can cover the costs of the requisite field work.

A second limitation relates to the potential cost of conducting Public Life Studies. In this instance, the project was well resourced, and an operating philosophy of the initiative was to fairly compensate everyone involved, rather than relying on volunteer labour. That said, the study was costly to undertake, and researchers considering these methods need to be strategic in the instances (which projects) and approach (how many study days) they deploy in PLS studies of this type. One aspect of this method where significant labour saving might be possible, would be in capturing field data using a digital interface (an app on a phone or tablet), which would avoid significant time during the data digitization phase.

An app could also presumably address the challenge of capturing data about a person observed on site straddling different hours of site observation, i. e.: someone who is present from say 9:45 – 10:15am, during two overlapping researcher shifts (9:00 – 10:00am and 10:00 – 11:00am). The analog approach employed required instances such as these to be

matched up and manually checked to ensure only one data line in the master spreadsheet versus two, whereas a shared digital platform for data entry could easily resolve this, by having that person's presence pre-populated when data collection is handed over from one researcher to the next. Efforts were made during the research design phase of this project to source such an application, without success.

Another opportunity that the researchers see for the communication of this data, is to move beyond two-dimensional print-based outputs into the animation of the data through time-lapse video formats, or to develop interactive web-based information graphics allowing the viewer to toggle between different variables and use sliders to move through time. Also, additional variables like sun/shade patterns could be mapped and analyzed spatially.

6 Conclusion

The pattern of middle-aged men clustering in the "without" condition and then visiting the site in a more distributed pattern in the "with condition" (Figure 5), would not have been revealed using traditional PLS data outputs that do not include a granular spatial analysis. This pattern represents one important finding about how the installations functioned as social infrastructure for middle aged men, a demographic group that tends to experience higher degrees of social isolation and loneliness than other groups, suggesting that the installation's design welcomed the group, and may have even encouraged interaction with other demographic groups. Indeed, an ethnographic study conducted as part of the research and complimenting the Public Life Study but beyond the scope of this article, involving interviews with site users, confirmed this finding.

The posters were designed to engage a broad public audience through display within an exhibition (large format) and within a public facing research report (8.5" x 11" format). plazaPOPS, the public space research initiative associated with this article, aims to create inclusive installations that welcome a more age and gender diverse group of users and support a wider range of social activities, and a goal of these visualizations was to clearly communicate the social performance of the subject public spaces to an audience of municipal staff and elected officials, as part of efforts to advocate for enabling policies to support the sustainable funding and growth of the initiative. While it is not yet clear the impact these visualizations will have on advancing the initiative, it was clear through informal observation and feedback during several public tours of the exhibition, that many visitors were compelled to study them carefully.

In summary, the datascapes presented in this paper that pair baseline and intervention-period public life data and represent spatial and temporal data in addition to conventional pie and bar charts can be a tool to communicate the social performance of public space design projects. As Public Life Studies continue to be mobilized to inform public space design and policy, the methods outlined in this paper can enhance design evaluation toward more particular insights about who the design is impacting, how, where, and for how long.

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From Visual Metrics to Public Perception: Mapping Nighttime Streetscapes in Nanjing's Old City, China

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Abstract: Nighttime streetscapes are critical to perceived safety and urban vitality, yet their perceptual quality remains difficult to quantify for planning and renewal. This study quantifies how image-derived visual metrics relate to public perception of nighttime streetscapes in Nanjing's Old City, China, and develops a street-level perception mapping framework. A total of 3,365 valid nighttime panoramic images were collected along the main road network. Fourteen objective visual metrics, covering brightness, color, and scene attributes, were computed for each image and mapped in GIS. Public perception of safety and aesthetics was assessed through a laboratory-based survey of selected images. Correlation analysis and stepwise regression were used to identify systematic relationships between visual metrics and perception. A Vision Transformer-based regression model was further trained to predict public perception of nighttime streetscapes. Together, these analyses demonstrate how interpretable visual metrics and data-driven modeling can be combined to quantify perceptual variation and support evidence-based diagnosis of nighttime street environments in historic urban areas.

Keywords: Nighttime streetscape, visual metrics, public perception, panorama, mapping

1 Introduction

Nighttime streetscapes shape perceptions of safety and comfort (FOTIOS et al. 2015) and influence whether people walk, stay, and engage with the city after dark (ZHU et al. 2023). Beyond roadway lighting, a growing body of nightscape research has examined how people evaluate nocturnal environments through affective impressions and experiential quality, including psychometric measurement tools such as the Nightscape Affect Index (GAO & ZHU 2025), evidence on fear-related responses under nighttime conditions (KIM et al. 2019), and studies showing that nighttime cityscape perceptions can differ from daytime readings in tourism and place evaluation contexts (HUANG & WANG 2018). In Nanjing's Old City, where historic street patterns and mixed everyday uses coexist, improving nighttime environments requires evidence that links visual experience to public perception, rather than relying on general claims of "better lighting" or "better design."

Existing research offers valuable insights but often separates measurable environmental properties from perception outcomes. Engineering-oriented studies emphasize physical quantities (WEI et al. 2025), while perception-oriented studies frequently rely on limited samples or less reproducible feature descriptions (KOO et al. 2022), making it difficult to compare results across streets and to support street-network diagnosis (FAN & BILJECKI 2024). Although nightscape studies increasingly connect subjective judgments with lighting and visual attributes – through protocols for sensorial perception and representation (ROBERT & FARHAT 2013), quantified links between subjective evaluation and objective lighting parameters (VALETTI et al. 2023), attention to chromatic appearance such as correlated color temperature (POURFATHOLLAH & MANDAVINEJAD 2020), and design-oriented evaluations of

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visitor satisfaction in nightscapes – many remain case-specific and do not yield a comparable, segment-level diagnostic basis for everyday street networks. This gap is especially relevant for old-city contexts, where spatial variation is strong and planning decisions require segment-level prioritization.

To address this need, we combine panoramic street-view imaging, reproducible visual metrics, a structured perception survey, and modeling that supports both explanation and mapping. We extract fourteen metrics across brightness, color, and scene attributes, and measure perception using six indicators in two dimensions, safety and aesthetics. We then quantify associations using correlation analysis and stepwise regression, and extend perception estimation beyond the surveyed subset using a Vision Transformer-based regression model (HOU et al. 2024) with GIS visualization. By linking visual metrics to perception and producing spatial outputs at the street-network scale, the study offers a practical basis for evaluating and improving nighttime streetscapes in Nanjing's Old City.

2 Material and Methods

2.1 Data Collection

This study focuses on Nanjing's Old City and acquires nighttime streetscape samples through street-scale field imaging (Figure 1). To standardize shooting conditions as much as possible and to improve route execution efficiency, we adopted a one-direction capture strategy. Specifically, the street interface was continuously recorded along a predefined travel direction, avoiding back-and-forth shooting that could introduce variation in nighttime lighting conditions and duplicate samples.

Fig. 1: Schematic diagram of research location

Panoramic street-view imagery was captured using an Insta360 X4 camera between December 15, 2024 and January 8, 2025, primarily from 19:00 to 21:00, when street lighting systems were fully operational. Images were collected at approximately 40 m intervals. Camera settings were fixed (ISO 6400, shutter speed 1/200 s, aperture f/1.9, auto white balance) to ensure consistent exposure and comparability across samples. In total, 3,378 nighttime panoramic images were obtained.

2.2 Objective Visual Metrics

To quantitatively characterize nighttime streetscapes, we constructed an indicator system consisting of 14 objective visual metrics derived from nighttime street-view images (Table 1). Following a light-color-scene framework, the metrics were grouped into brightness (n=4), color (n=5), and scene attributes (n=5), capturing illumination conditions, chromatic organization, and spatial composition.

Table 1: Objective visual metrics and semantic labels

Category	Metrics	Category	Metrics	Semantic Labels
1) Brightness Metrics	Mean Luminance	3) Scene Metrics	Spatial Enclosure, SE	Building
				Wall
	Luminance Contrast			Fence
				Pole
	High-luminance Spot Area Ratio, HSAR		Green View Index, GVI	Vegetation
				Terrain
			Sky View Factor, SVF	Sky
	High-luminance Spot Count, HSC		Non-motorized View Index, NVI	Person
				Sidewalk
				Rider
				Bicycle
2) Color Metrics	Mean CIELAB a*, Red-Green		Motorized View Index, MVI	Road
				Traffic Light
	Mean CIELAB b*, Yellow-Blue			Traffic Sign
				Car
				Truck
	Mean Color Saturation, S			Bus
	Color Complexity			Motorcycle
	Color Harmony			Train

1) Brightness metrics describe overall luminance level, luminance variation, and localized high-intensity lighting, including Mean Luminance, Luminance Contrast, High-luminance Spot Area Ratio (HSAR), and High-luminance Spot Count (HSC).
2) Color metrics include Mean CIELAB a* (red-green), Mean CIELAB b* (yellow-blue), Mean Color Saturation, Color Complexity, and Color Harmony. While a*, b*, and saturation characterize overall chromatic tendency and intensity, Color Complexity and Color Harmony, derived from color composition and dominant-color organization (CHEN et al. 2025) – capture differences in visual richness and chromatic coordination.

3) Scene metrics are derived from semantic segmentation and aggregated into five composite features: Spatial Enclosure (SE), Green View Index (GVI), Sky View Factor (SVF), Non-motorized View Index (NVI), and Motorized View Index (MVI). These metrics represent interface enclosure, greenery visibility, openness, and the relative presence of traffic-related elements in nighttime street space.

2.3 Preprocessing and Extraction

To ensure geometric consistency across samples, all panoramic images were first standardized and cleaned (Figure 2). Because equirectangular projection introduces pixel-area distortion, images were converted to cylindrical equal-area projection using Mathematica (ZHANG et al. 2019). Low-quality samples (e. g., severe blur, exposure anomalies, occlusion, or missing metadata) were removed, resulting in 3,365 valid images.

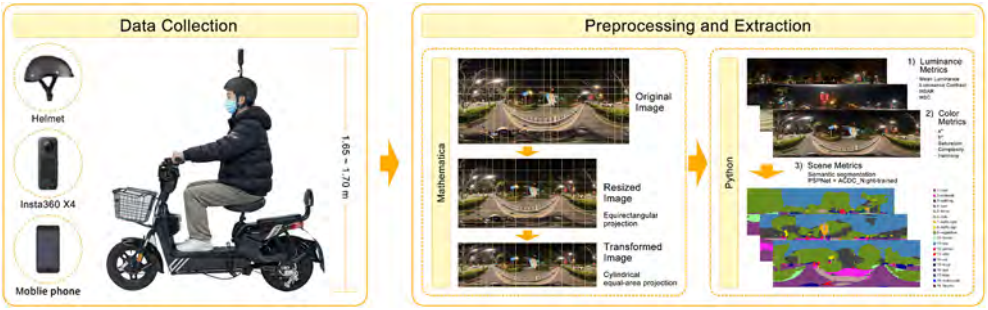

Fig. 2: Nighttime streetscape panorama data collection, preprocessing and extraction

The standardized images were then used to extract 14 objective visual metrics. Luminance metrics were derived using pixel-level statistics and threshold-based segmentation in Python. Color metrics were obtained by combining pixel-level statistics in CIELAB space with K-means clustering of dominant colors to derive Color Complexity and Color Harmony.

Scene metrics were extracted using deep-learning-based semantic segmentation. We applied PSPNet trained on the ACDC_Night dataset with Cityscapes-compatible labels to improve robustness under nighttime conditions (LIU et al. 2023). Class-wise pixel proportions were aggregated into five scene features (SE, GVI, SVF, NVI, and MVI), which served as quantitative inputs for subsequent analyses.

2.4 Perception Survey

To collect public perceptual evaluations of nighttime streetscapes, we conducted an image-based survey experiment. From the quality-controlled image set, 300 samples were selected at equal spatial intervals to ensure representativeness across the study area. The images were randomly assigned to 50 questionnaires, each containing a subset of samples. To improve rating stability, each image was evaluated five times by different participants, yielding multiple independent ratings per sample.

Perception was measured along two dimensions – Safety and Aesthetics – each represented by three indicators (Table 2). Safety included Lighting Safety (S1), Visual Openness (S2), and Traffic Safety (S3), while Aesthetics comprised Interface Diversity (A1), Color Pleasant-

ness (A2), and Vegetation Richness (A3). Participants rated each image on all six items using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree).

A total of 50 participants were recruited, including a professional student group (n = 25) and a general public group (n = 25), with balanced gender composition and an age range of 18–55 years. Individuals with visual, cognitive, or health conditions that could affect judgment were excluded. The resulting ratings provided the basis for reliability assessment, score aggregation, and subsequent modeling.

Table 2: Public perception indicators and codes

Dimensions	Perception Indicators	Indicator Codes
Safety	Lighting Safety	S_1
	Visual Openness	S_2
	Traffic Safety	S_3
Aesthetics	Interface Diversity	A_1
	Color Pleasantness	A_2
	Vegetation Richness	A_3

2.5 Analysis and Modeling

To ensure the stability and usability of survey ratings, inter-rater agreement and internal consistency were assessed. Intraclass correlation coefficients (ICC) were calculated for repeated ratings of the same image, and McDonald's ω and Cronbach's α were used to evaluate internal consistency within perception dimensions. When reliability was acceptable, ratings were averaged to obtain image-level scores; otherwise, robust aggregation or outlier removal was applied.

Prior to statistical modeling, objective metrics exhibiting strong skewness were transformed to improve distributional form, and all 14 metrics were standardized using Z-scores. Pearson correlation analysis was then conducted to examine (i) relationships among objective metrics, (ii) associations among perception indicators, and (iii) linkages between visual metrics and perception, with collinearity diagnostics used to screen redundant predictors.

Stepwise multiple linear regression was performed to model each of the six perception indicators separately, treating the 14 visual metrics as candidate predictors. Bidirectional selection was applied with entry and removal thresholds of $p < 0.05$ and $p > 0.10$, respectively. Final models were reported as regression equations, allowing comparison of key predictors and effect directions across indicators.

To complement explanatory regression with prediction-oriented modeling, we developed a Vision Transformer (ViT) regression model to capture potential nonlinearity and interaction effects. Survey-derived image-level scores served as supervision. To improve training stability with limited labels, images were augmented through projection conversion and horizontal mirroring, expanding the labeled dataset to 1,200 samples. The data were split into training and validation sets (80%/20%), and separate models were trained for each perception indicator. Predicted scores were then linked to image locations and visualized in GIS to reveal spatial disparities across the street network.

3 Results

3.1 Mapping of Objective Visual Metrics

Descriptive statistics for the 14 objective visual metrics are summarized in Table 3. Mean Luminance and Luminance Contrast show relatively concentrated distributions with clear central tendencies, indicating moderate variation in nighttime lighting across the study area. By contrast, HSAR and HSC are strongly right-skewed with upper outliers, suggesting that intense localized lighting is confined to a small subset of street segments.

Table 3: Descriptive statistics of the objective visual metrics

Objective Metrics	N	Median	Mean	Std. Deviation	Minimum	Maximum
Mean Luminance	3365	61.22	62.62	23.461	4.378	132.9
Luminance Contrast	3365	47.22	46.971	10.464	10.59	74.64
HSAR	3365	0.001	0.004	0.007	0	0.099
HSC	3365	15	21.696	19.798	0	162
Mean CIELAB a*	3365	2.43	2.663	1.815	-9.38	22.18
Mean CIELAB b*	3365	4.64	4.428	3.718	-21.08	21.73
Mean Color Saturation	3365	84.49	87.512	20.795	21.56	171.8
Color Complexity	3365	0.662	0.643	0.083	0.083	0.747
Color Harmony	3365	0.8	0.788	0.422	0.0005	2.126
SE	3365	27.716	28.329	10.031	3.018	64.65
GVI	3365	19.233	19.963	12.369	0	73.12
SVF	3365	8.38	10.288	8.751	0	41.87
NVI	3365	6.696	7.275	4.794	0	30.68
MVI	3365	33.291	34.145	7.893	8.677	89.66

Color metrics display substantial heterogeneity. Mean CIELAB a* and b* span both positive and negative values, indicating bidirectional shifts in chromatic tendency. Mean Color Saturation shows greater dispersion, reflecting variability in lighting color appearance across streets. Among dominant-color-derived metrics, Color Complexity exhibits relatively limited variation, whereas Color Harmony spans a wider range with more pronounced outliers, indicating that variation in chromatic coordination is more salient than differences in compositional richness.

Scene metrics also show marked heterogeneity. Several metrics approach zero for certain segments, indicating very low visibility of specific scene elements, while upper outliers suggest that strong enclosure, openness, greenery, or traffic presence is concentrated in a small number of streets.

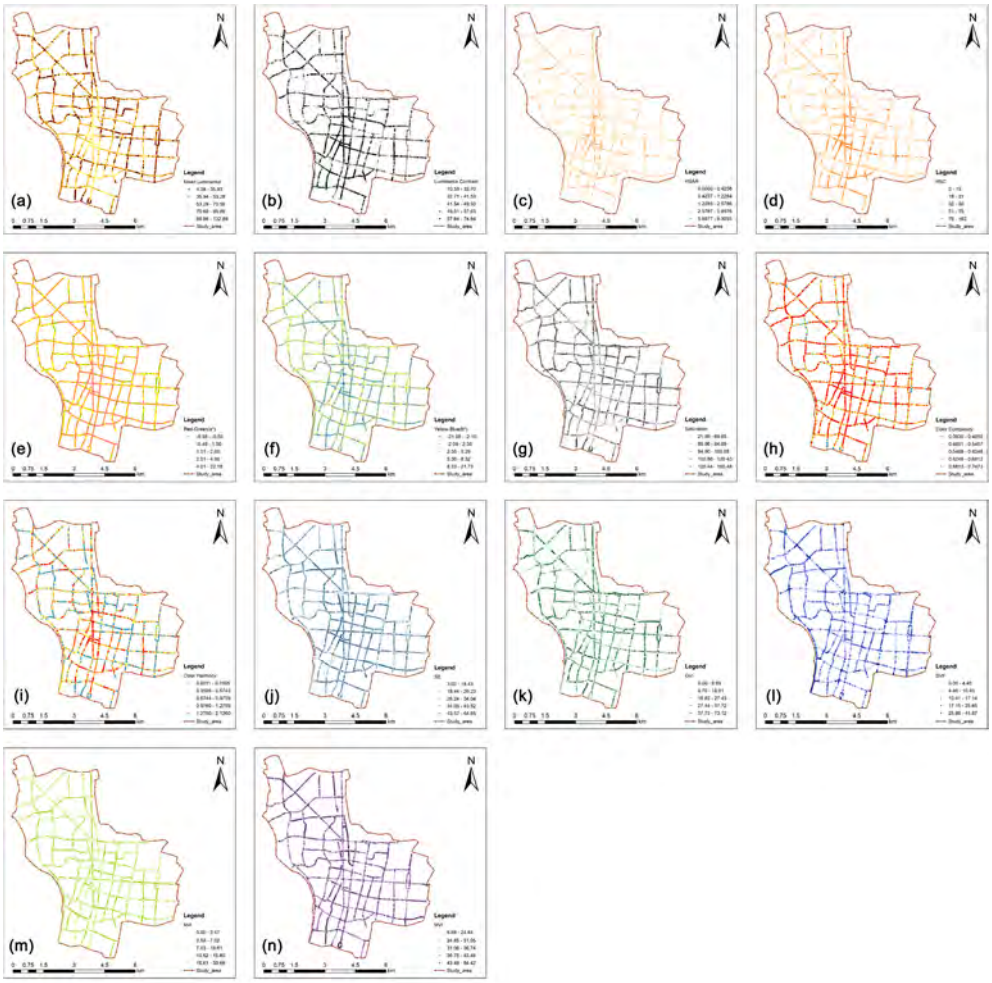

Fig. 3: Visualization of the 14 objective visual metrics:
(a) Mean Luminance, (b) Luminance Contrast, (c) HSAR, (d) HSC, (e) Mean CIELAB a*, (f) Mean CIELAB b*, (g) Mean Color Saturation, (h) Color Complexity, (i) Color Harmony, (j) SE, (k) GVI, (l) SVF, (m) NVI, (n) MVI

Spatial mapping reveals clear non-uniform patterns across all metrics (Figure 3). Luminance-related metrics are generally higher along major road corridors, whereas HSAR and HSC form localized hotspots at specific segments or nodes. Color metrics exhibit alternating linear and patchy patterns, and scene metrics reflect differences in street morphology and element composition. Overall, the metrics vary in complementary rather than uniform directions, providing an intuitive basis for identifying weaker street segments and proposing targeted nighttime improvement strategies.

3.2 Reliability of Public Perception

Survey reliability was assessed in terms of inter-rater agreement and internal consistency. Single-rating reliability (ICC(1,1)) ranged from 0.385 to 0.777, with higher values for Vegetation Richness (A3) and Lighting Safety (S1) and lower values for Color Pleasantness (A2). When five ratings were averaged for each image, ICC(1,5) increased substantially to 0.758–0.946, indicating high agreement across all indicators.

Internal consistency analysis yielded McDonald's $\omega = 0.759$ (95% CI: 0.717–0.801) and Cronbach's $\alpha = 0.725$ (95% CI: 0.677–0.772), both within acceptable ranges. These results support the use of five-rater mean scores as stable image-level perception measures for subsequent analyses.

3.3 Associations Between Visual Metrics and Perception

3.3.1 Correlation

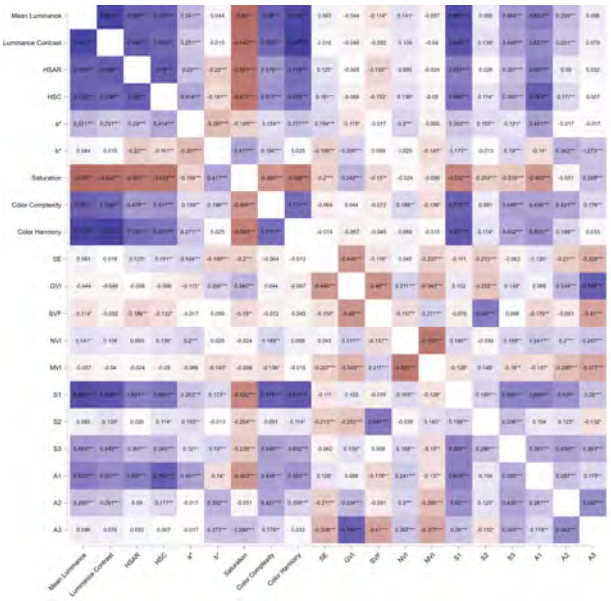

Fig. 4:
Correlation matrix of objective visual metrics and subjective perception indicators (Pearson's r; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

The correlation matrix between objective metrics and perception indicators is shown in Figure 4. Among objective metrics, luminance-related variables are strongly correlated, with Mean Luminance and Luminance Contrast exhibiting the highest association ($r = 0.923$). Both are positively related to HSAR and HSC, indicating that brighter scenes tend to display more localized high-luminance effects. Color Saturation is consistently negatively correlated with luminance-related metrics, suggesting a more desaturated appearance under stronger lighting conditions.

Scene metrics reveal structural trade-offs, including negative correlations between NVI and MVI ($r = -0.597$) and between GVI and SVF ($r = -0.480$). Within perception dimensions, indicators show stronger intra-dimension correlations than cross-dimension associations. Across dimensions, Lighting Safety is positively related to several aesthetic indicators, whereas Visual Openness exhibits weaker or negative associations with Vegetation Richness.

Associations between objective metrics and perception indicators are differentiated by perceptual dimension. Lighting Safety is most strongly related to luminance and color-organization metrics, Visual Openness is driven primarily by spatial structure, and Vegetation Richness is closely associated with GVI. These patterns motivate subsequent regression modeling and highlight the need to control multicollinearity among luminance variables.

Table 4: Stepwise regression results

Objective metrics	**Transform**	**S1**	**S2**	**S3**	**A1**	**A2**	**A3**
Mean Luminance	–	0.788	–	0.385	–	–	0.190
Luminance Contrast	–	–	–	–	–	–	–
High-luminance Spot Area Ratio	$\log_{10}(x+1)$	–	–	–	–	–	–
High-luminance Spot Count	$\log_{10}(x+0.0001)$	–	0.137	–	0.743	–	–
Mean CIELAB a*	–	–	0.099	–	0.152	–	–
Mean CIELAB b*	–	0.066	–	0.088	–	0.202	–
Mean color Saturation	$\log_{10}(x+1)$	–	–	–	–	-0.148	0.221
Color Complexity	x^3	0.144	–	–	–	0.239	0.102
Color Harmony	–	–	–	–	–	-0.107	–
Spatial Enclosure	$\log_{10}(x+1)$	-0.170	-0.159	–	–	–	–
Green View Index	$\log_{10}(x+1)$	–	–	0.167	0.116	0.186	0.753
Sky View Factor	$\log_{10}(x+1)$	–	0.517	0.132	–	–	–
Non-motorized View Index	$\log_{10}(x+1)$	–	–	–	0.089	–	–
Motorized View Index	$\log_{10}(x+1)$	-0.083	–	–	–	-0.076	-0.103
Intercept	–	3.740	3.613	3.313	2.954	3.252	3.342
Adjusted R^2	–	*0.830*	*0.496*	*0.291*	*0.652*	*0.352*	*0.657*
RMSE	–	*0.413*	*0.542*	*0.633*	*0.603*	*0.531*	*0.631*
N	–	300	300	300	300	300	300

Note. All variables undergo Z-score normalization after transformation before regression analysis.

3.3.2 Stepwise Regression

Stepwise regression selected key explanatory variables from the 14 objective nightscape metrics and established separate regression models for the six subjective perception indicators (Table 4). Because predictors were Z-score standardized after the necessary mathematical transformations, the coefficients reported in the table can be used to compare the relative direction and magnitude of different objective metrics' contributions to each perception indicator.

3.3.3 Machine Learning

In the explanatory stepwise regression models, fit varied substantially across indicators (RMSE = 0.413–0.633; Adjusted R^2 = 0.291–0.830). Indicators such as Traffic Safety (S3)

and Color Pleasantness (A2) showed relatively limited linear fit, suggesting that visual-perception relationships may involve nonlinearity and interactions. In comparison, the ViT regression model achieved more favorable and more stable performance on an independent test set (RMSE = 0.382–0.551; R^2 = 0.436–0.853), outperforming stepwise regression overall (Table 5). We therefore used machine learning as a prediction-oriented pathway to extend limited survey labels into perception estimates with full coverage of the study area, supporting macro-level diagnosis and segment- and district-specific improvement strategies.

After linking the six predicted scores to sample locations, we produced road-network perception maps in ArcGIS. Safety-related indicators tended to form more continuous corridor-like gradients with localized high/low clusters, whereas Aesthetics-related indicators were more fragmented. Some segments showed synchronized variation in Interface Diversity, Color Pleasantness, and Vegetation Richness, while others did not.

Table 5: Machine-learning model performance on the validation set

Machine-Learning Models	N	MSE	RMSE	MAE	MAPE, %	R^2
Lighting Safety (S1)	240	0.153	0.391	0.276	8.815	0.853
Visual Openness (S2)	240	0.146	0.382	0.305	9.095	0.729
Traffic Safety (S3)	240	0.242	0.492	0.389	13.983	0.550
Interface Diversity (A1)	240	0.191	0.437	0.358	15.675	0.787
Color Pleasantness (A2)	240	0.280	0.529	0.443	15.893	0.436
Vegetation Richness (A3)	240	0.304	0.551	0.431	15.954	0.722

4 Discussion

The stepwise regression results indicate that different perception indicators align with different visual mechanisms. Lighting safety is most strongly associated with brightness conditions and with visual organization cues, suggesting that perceived safety depends on both overall visibility and how light is distributed in the scene. Visual openness is more sensitive to spatial-structure cues, particularly sky visibility and enclosure-related attributes, than brightness alone. This pattern is consistent with prior findings (LI et al. 2022). Vegetation richness is largely explained by green visibility (GVI) in our models, while aesthetic judgments also reflect how color and scene composition are organized (SONG et al. 2025). The stepwise model reveals a negative effect of Color Harmony on color pleasantness, as it reflects a more uniform and potentially color monotonous appearance when saturation and complexity are controlled.

These findings support street-level implications for nighttime renewal in Nanjing's Old City. For safety-related experience, improving visual legibility can be as important as increasing illumination, highlighting the value of reducing extreme highlights, enhancing continuity along walking corridors, and coordinating chromatic appearance. For perceived openness, interventions that clarify sightlines and manage enclosure cues may be more effective than simply raising brightness. For aesthetic quality, vegetation visibility and controlled color composition emerge as key levers, informing planting strategies and heritage-sensitive lighting coordination at the segment scale.

Interpreting the GIS maps of predicted perception scores in relation to the four historic districts provides a planning-oriented reading of the model outputs (Figure 5). The district context helps clarify where perceived safety and aesthetic quality are relatively stronger or weaker across the old-city street network, offering an empirical basis for district-level prioritization in renewal and management.

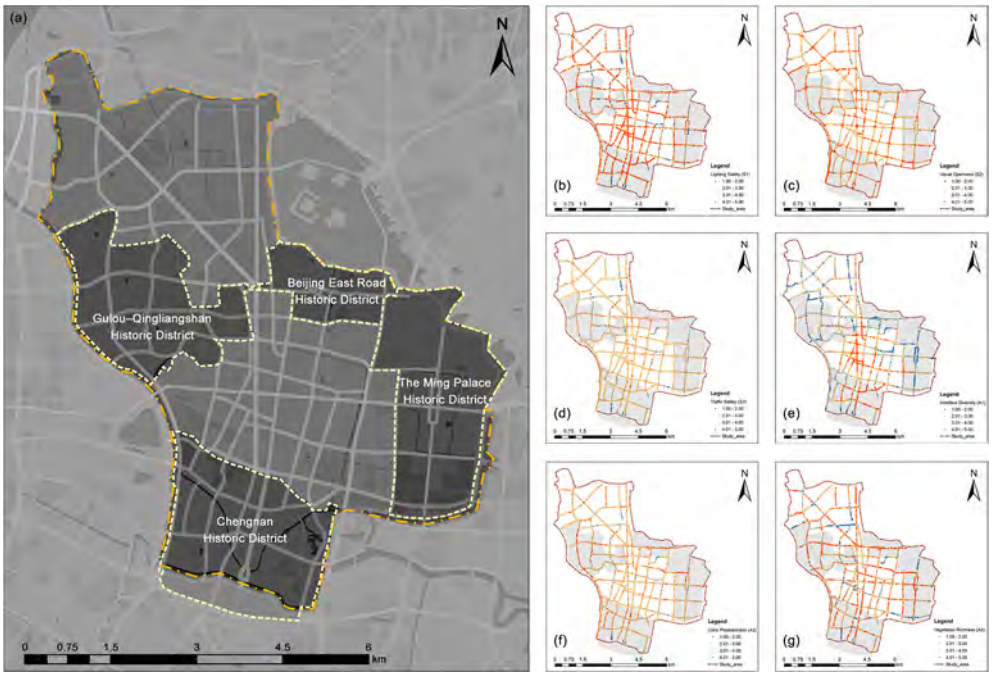

Fig. 5: Spatial distribution of historic districts in Nanjing's old city and machine-learning predicted perception scores (S1–A3)
(a) Historic districts in Nanjing's Old City; (b) Lighting Safety, S1; (c) Visual Openness, S2; (d) Traffic Safety, S3; (e) Interface Diversity, A1; (f) Color Pleasantness, A2; (g) Vegetation Richness, A3

Distinct perceptual patterns emerge across the four historic districts. Chengnan exhibits a higher concentration of segments with favorable safety-related scores, particularly for lighting safety and visual openness, alongside stronger aesthetic ratings along key corridors, consistent with more continuous nighttime visibility and legible street scenes. In contrast, the Beijing East Road district contains several segments with relatively low traffic-safety scores, suggesting that motor-dominant corridors and complex intersections remain key perceptual constraints. The Gulou-Qingliangshan district shows comparatively strong vegetation-related aesthetics, reflecting hillside and park-adjacent settings that enhance nighttime green visibility. The Ming Palace district is more heterogeneous, with lower scores for interface diversity and vegetation richness along certain corridors, indicating constraints related to uniform frontages or reduced perceived greenery. Together, these contrasts imply differentiated renewal priorities across districts.

This district-based interpretation should be read as a planning-oriented synthesis rather than a strict zonal statistic. The maps visualize model-predicted scores derived from image-based inputs, and a more rigorous comparison across the four districts would require aggregating segment-level predictions within each district boundary and reporting means and uncertainty (WADOUX & HEUVELINK 2023). In addition, perception was measured through images rather than in-situ experience, and the data reflect a specific sampling period and one-direction capture strategy, which may not fully represent temporal variation or bidirectional pedestrian viewpoints across all streets (CURTIS et al. 2013).

5 Conclusion and Outlook

This study provides an end-to-end workflow to link visual metrics with public perception in nighttime streetscapes of Nanjing's Old City. Based on a large panoramic image dataset, fourteen objective metrics were extracted across brightness, color, and scene attributes, and six perception indicators were obtained from repeated public ratings with demonstrated reliability. Statistical analysis and stepwise regression quantified indicator-specific associations, and a Vision Transformer-based regression model produced network-wide perception predictions that were mapped in GIS. The workflow supports evidence-based diagnosis of spatial disparities in nighttime perception and helps prioritize street segments for renewal. Future research should incorporate multi-temporal sampling, on-site validation, and cross-city replication, and should further explore models that capture nonlinearity while retaining interpretability for planning and design practice.

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Participatory Design, Community Engagement and User Experience

ElderSim: A Human-Centric Multi-Agent Planning Simulator for Adaptive Optimization of Community Sports Facilities

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Abstract: This study develops ElderSim, a human-centric agent-based simulation framework to model elderly users' interactions with community sports facilities. The EOFIR behavioral ruleset captures movement, facility choice, social interaction, and activity persistence. Using ARTISOC Cloud, simulation outputs are coupled with a genetic algorithm to optimize layouts for efficiency and equity. Results demonstrate how spatial configuration influences activity intensity and fairness, providing planners with data-driven decision support. This framework advances digital planning tools for aging communities by integrating behavioral realism with adaptive optimization.

Keywords: Agent-based modeling, human-centric design, adaptive optimization, community sports facilities, behavioral simulation

1 Introduction

1.1 Background

Population aging has become a defining global demographic trend, profoundly shaping urban planning and public health agendas. As the proportion of elderly citizens continues to rise worldwide, the demand for inclusive and health-promoting community infrastructures is growing accordingly. Among these infrastructures, community sports facilities play a crucial role in supporting physical well-being, encouraging social participation, and promoting active lifestyles for older adults.

In recent years, many cities – including those in China – have made remarkable progress in improving the accessibility and quality of community sports spaces. However, as elderly users' behavioral diversity and spatial preferences become more complex, planners are increasingly challenged to ensure that facilities not only meet general accessibility standards but also respond to subtle variations in individual needs, mobility patterns, and social interactions. This calls for a more refined, data-informed approach to spatial design and policy-making.

Traditional planning methods, which rely primarily on aggregated statistics and expert judgment, often struggle to capture the dynamic interactions between elderly users and their built environments. Emerging digital tools, particularly agent-based modeling (ABM), offer new possibilities for bridging this gap. ABM enables researchers to simulate individual decision-making processes and observe how micro-level behaviors collectively influence the performance of urban systems.

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Building upon these developments, this study introduces ElderSim, a human-centric multi-agent simulator designed to model elderly users' interactions and adaptive behaviors within community sports facilities. By integrating behavioral data and digital optimization techniques, the research aims to enhance both the efficiency and inclusivity of facility layouts – contributing to the broader goal of creating resilient and age-friendly communities.

1.2 Spatial and Behavioral Studies

Previous studies have shown that spatial configuration strongly influences older adults' physical activity and social participation. The environmental press-competence model (LAWTON & NAHEMOW, 1973) laid the foundation for understanding how built environments shape aging behavior. Later works such as SUGIYAMA & THOMPSON (2008) and KERR et al. (2012) confirmed that walkability, greenery, and resting points significantly enhance outdoor activity. In China, scholars including HUANG et al. (2018) and WANG et al. (2020) found that the accessibility and density of community sports facilities directly affect elderly residents' exercise frequency, while ZHAO et al. (2019) emphasized the value of multifunctional and socially engaging spaces.

However, most existing research implicitly assume that users behave independently and that facility demand remains stable over time. In practice, elderly users continuously adjust their behavior in response to the presence of others, resulting in dynamic interactions that are rarely captured by static spatial analysis or survey-based methods.

In this study, dynamic interactions refer to the real-time behavioral coupling among elderly users competing for shared facilities. These interactions mainly include facility competition (e. g., queueing, congestion avoidance, and waiting), social attraction (e. g., joining familiar or visible groups), and behavioral feedback (e. g., modifying routes, activity duration, or facility choice based on perceived crowding or fatigue). Such interactions emerge naturally in community sports spaces because elderly users often share limited facilities, exhibit heterogeneous physical capacities, and place high value on social presence and comfort. The absence of these dynamics leads to a critical gap in existing planning approaches. Facilities that appear efficient or equitable under static evaluation may become congested or underutilized once real-time user competition and behavioral adaptation are considered. As a result, planners lack tools to assess how spatial layouts perform under realistic, interaction-driven usage conditions. To address this gap, this research proposes a human-centric simulation framework that explicitly models dynamic user interactions and competitive facility selection behavior among elderly residents. By embedding these mechanisms into an agent-based environment, the study moves beyond static accessibility analysis and enables planners to evaluate and optimize community sports facilities based on emergent behavioral outcomes.

1.3 Agent-Based Modeling Studies

Agent-Based Modeling (ABM) provides a bottom-up framework to simulate how individual behaviors generate complex spatial outcomes. Early models such as the social force model (HELBING & MOLNAR 1995) and TORRENS (2012)'s pedestrian simulations demonstrated ABM's potential in capturing adaptive human movement. In recent years, ABM has been integrated with GIS and optimization tools to study urban dynamics, yet applications in community facility planning remain limited.

Domestic researchers have begun exploring this direction. CHEN et al. (2020) and LI (2021) applied ABM to evaluate accessibility and spatial allocation of community sports facilities, but their models lacked behavioral feedback and adaptive optimization. Building on these foundations, this study introduces ElderSim, a human-centric multi-agent simulator that embeds real behavioral rules of elderly users. By combining participatory scenario testing with a three-stage Adaptive Optimization process, ElderSim transforms ABM from a descriptive tool into a decision-support platform for community sports facility design.

1.4 Aim

This study aims to develop ElderSim, a human-centric agent-based simulation tool for optimizing elderly-oriented community sports facilities. By integrating behavioral data with a three-stage Adaptive Optimization process – baseline modeling, participatory scenario testing, and genetic algorithm-based auto-optimization – ElderSim enables planners to evaluate and refine facility layouts dynamically, promoting efficiency, equity, and inclusiveness in aging urban environments. Furthermore, ElderSim extends traditional ABM frameworks by embedding a behaviorally grounded ruleset derived from field data, which forms the foundation for the methodological development discussed in the following section.

2 Methodology

2.1 Data Collection

Additionally, we conducted systematic observations of the layout of community sports facilities, recording the elderly's usage behaviors, duration of stay, movement paths, and social interaction patterns. These data provide foundational parameters for constructing an agent-based simulation model.

The empirical foundation of ElderSim was established through field investigation and semi-structured interviews conducted in Jianhua First Community, Chang'an District, Shijiazhuang. The study combined direct behavioral observation with qualitative interviews to un-

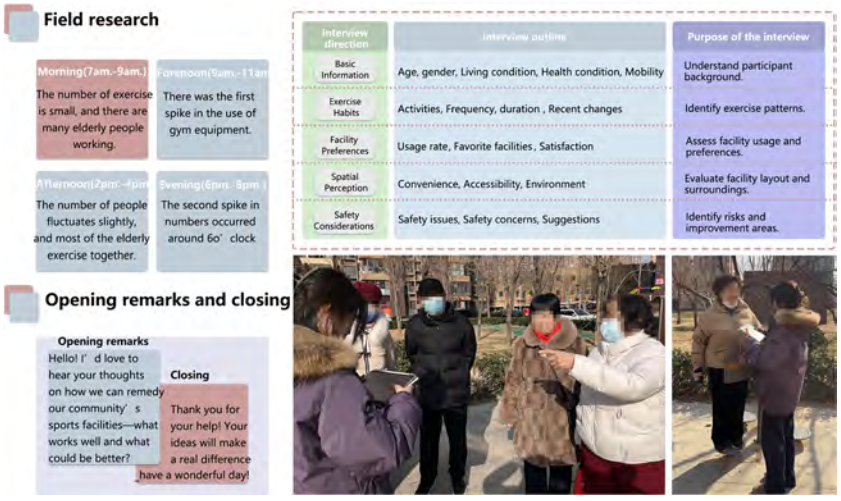

Fig. 1: Research process

derstand elderly residents' use of community sports facilities, movement patterns, and spatial preferences.

Ten participants aged over sixty were interviewed, covering topics such as daily exercise routines, preferred facility types, social interactions, route choices, and safety concerns. The interviews were used to extract recurring behavioral patterns rather than statistically representative distributions. Parallel to the interviews, on-site observations were carried out to record activity duration, movement trajectories, and social clustering in different facility zones. (shown as Fig. 1) These mixed data provided both quantitative and qualitative inputs for constructing the Elderly-Oriented Facility Interaction Ruleset in the subsequent modeling stage.

2.2 Behavioral Ruleset Construction (EOFIR)

The Elderly-Oriented Facility Interaction Ruleset (EOFIR) was designed to capture how elderly users dynamically make activity decisions within shared community sports spaces. Instead of reproducing individual biographies, EOFIR abstracts recurring behavioral mechanisms derived from field observation and semi-structured interviews into a set of transferable rules. These rules were implemented in the Artisoc Cloud agent-based simulation environment using its event-based behavioral logic.

EOFIR consists of four interdependent rule categories: mobility rules, facility selection rules, social interaction rules, and activity persistence rules. Together, they describe how elderly agents move through space, compete for facilities, interact socially, and regulate activity duration under physical and environmental constraints (Fig. 2).

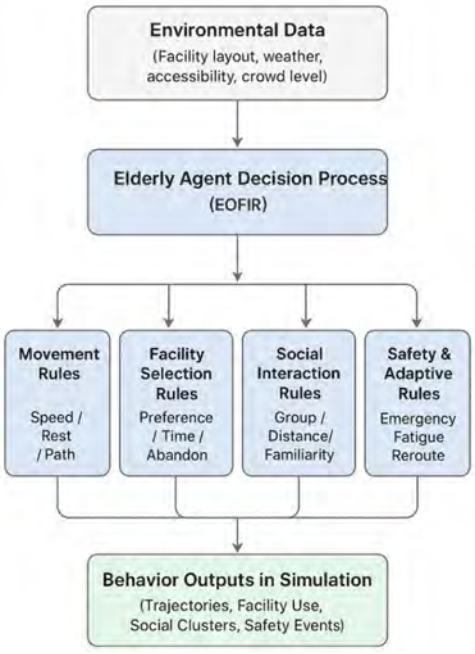

Fig. 2: Ruleset

1) Mobility Rules. Mobility rules govern how agents navigate the community environment. Each agent is assigned an age-dependent walking speed within a predefined range (0.8-1.2 m/s) to reflect heterogeneous physical capacity. Route selection prioritizes barrier-free and shaded paths over purely shortest-distance routes, reflecting observed preferences for comfort and safety. As agents move, cumulative physical fatigue increases based on walking distance and activity intensity. Once fatigue exceeds a threshold, agents actively seek nearby resting facilities before continuing their activities. These rules allow walking trajectories and pauses to emerge adaptively rather than being predefined;
2) Facility Selection Rules. Facility selection rules determine how agents choose, abandon, or switch between sports facilities. Each agent evaluates available facilities based on three weighted factors: spatial proximity, perceived waiting time (approximated by current occupancy), and familiarity derived from previous successful use. When facility occupancy exceeds its service capacity, agents respond differently by queuing, relocating to alternative facilities, or reducing planned activity duration. This mechanism explicitly represents competition for shared facilities, enabling congestion and redistribution patterns to emerge from individual decision-making;
3) Social Interaction Rules. Social interaction rules capture the influence of social presence on elderly activity behavior. Agents are more likely to engage in activities at locations where familiar individuals or visible groups are present, reflecting the motivational role of companionship and collective exercise. However, group size is constrained to prevent excessive crowding and discomfort. Through this rule, collective patterns such as spontaneous group formation and socially preferred facilities emerge without being predefined, reinforcing the human-centric nature of the simulation;
4) Activity Persistence Rules. Activity persistence rules regulate how long agents remain engaged in a selected activity. Persistence is influenced by a combination of physical fatigue, social engagement, and environmental comfort. Activities are prolonged when agents participate within familiar groups or in comfortable micro-environments, while high congestion or accumulated fatigue accelerates activity termination. This rule links behavioral motivation with physical endurance, enabling the simulation to generate differentiated activity durations and, consequently, varied energy expenditure outcomes.

By integrating these four rule categories, EOFIR enables ElderSim to simulate adaptive and interaction-driven behavior within realistic community settings. At the same time, the framework maintains a balance between behavioral complexity and computational efficiency. The model does not aim to represent the full spectrum of elderly fitness lifestyles, but rather focuses on everyday, neighborhood-based activities where spatial configuration plays a decisive role. While EOFIR primarily focuses on neighborhood-scale, walkable activities, it acknowledges that long-distance, car-based fitness routines and instructor-led programs represent an important extension for future multi-scale modeling.

2.3 ElderSim Development Framework

The development of ElderSim integrates empirical behavioral logic with agent-based modeling to simulate elderly users' interactions with community sports facilities. The framework follows a three-stage process (Fig. 3), combining data-driven initialization, behavior simulation, and feedback-based optimization.

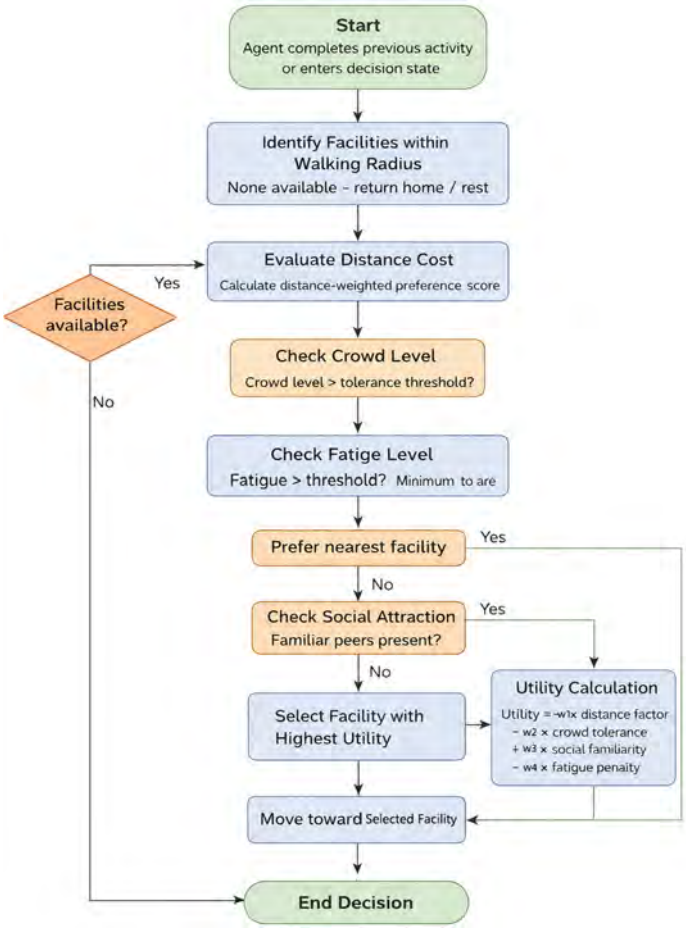

Fig. 3: Decision Flow of the Facility Selection Rule in EOFIR

Stage One: Crowd and Facility Initialization

Elderly agents and facility agents are generated based on demographic and spatial data from the field survey. Each agent is assigned attributes such as activity level, mobility, and demand preference, while facilities carry parameters of type, capacity, and location. Initial spatial positions are set according to the actual layout of Jianhua First Community, ensuring spatial realism.

Stage Two: Travel and Facility Use

Agents dynamically generate activity needs according to the frequency and time-period distributions derived from the survey. They assess reachable facilities using the EOFIR decision ruleset – evaluating travel distance, facility utility, and social interaction probability – to select optimal activity locations. Facility agents track user load and respond to crowding by limiting access or altering availability. The simulation records behavioral outputs such as trajectories, use duration, and participation rates.

Stage Three: Return and Feedback Adjustment

After each use cycle, agents update their satisfaction and utility parameters, influencing subsequent decisions. The system aggregates statistics on walking time, facility utilization, and

equity of access, providing inputs for the adaptive optimization stage. These outputs enable planners to evaluate layout performance under varying design scenarios and guide automated search for Pareto-optimal solutions in the next section.

The ElderSim model was implemented and executed on the Artisoc Cloud platform, which provides a visual and programmable environment for multi-agent simulation. The behavioral rulesets and spatial parameters were imported as configuration modules, and the simulation outputs – agent trajectories, facility utilization rates, and interaction networks – were dynamically visualized during runtime (Fig. 4).

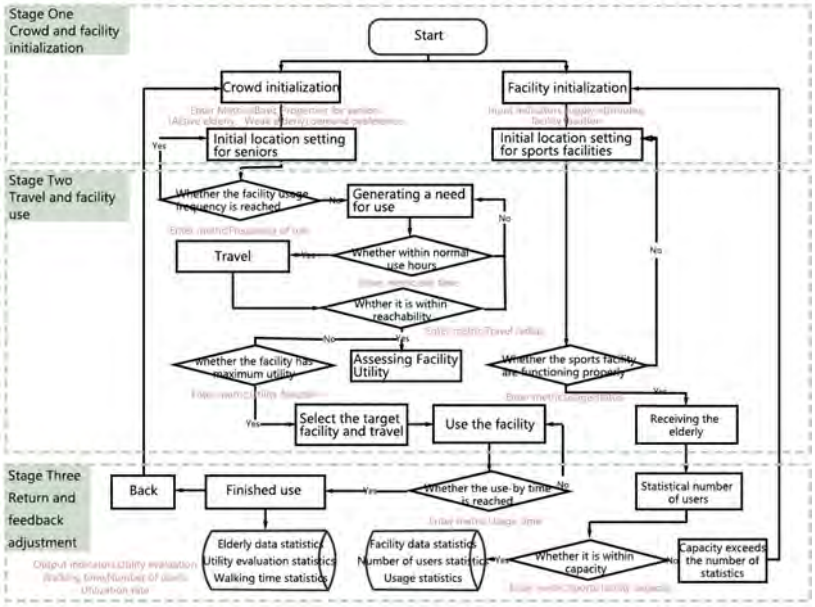

Fig. 4: Simulation process

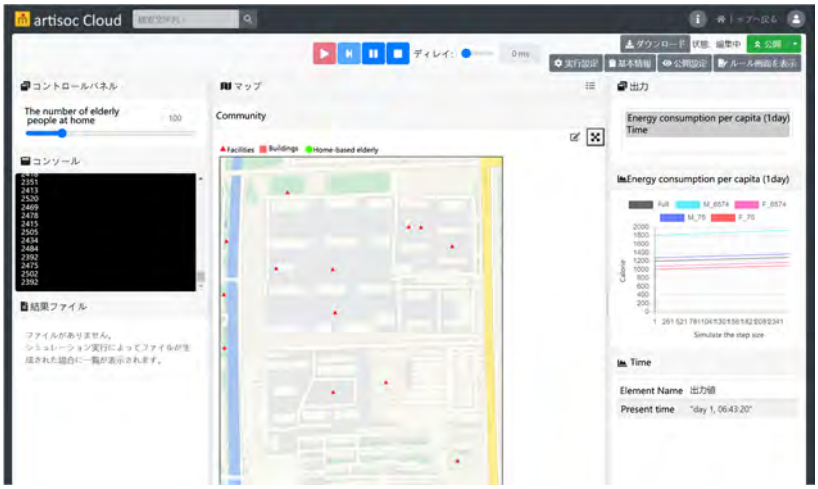

Fig. 5: Agent simulation of Artisoc Cloud

2.4 Adaptive Optimization Process

To extend ElderSim from behavioral simulation toward planning support, an adaptive optimization module based on a Genetic Algorithm (GA) was integrated into the framework. The optimization aims to explore alternative facility layouts that improve both spatial efficiency and user equity under realistic, interaction-driven usage conditions.

In the optimization process, the decision variables include the spatial location, functional type, and service capacity of community sports facilities. Each candidate layout generated by the GA is evaluated through a full ElderSim simulation, producing behavioral outputs at both individual and aggregate levels. Among these outputs, calorie consumption is used as the primary proxy for physical activity intensity.

Two performance objectives are defined. Efficiency (E) is measured as the normalized average calorie consumption across all agents, reflecting the overall vitality of elderly physical activity. Equity (Q) is quantified using the complement of the Gini coefficient of calorie consumption distribution, capturing how evenly physical activity benefits are distributed among users. The composite fitness function is formulated as:

$$F=\alpha\cdot E+\beta\cdot Q$$

where α and β represent weighting parameters that balance efficiency and equity. In this study, equal weights ($\alpha=\beta=0.5$) are adopted to avoid prioritizing aggregate performance at the expense of disadvantaged user groups.

Through iterative operations of selection, crossover, and mutation, the GA searches the solution space for layouts that maximize the composite fitness value. Rather than producing a single optimal solution, the optimization yields a set of Pareto-efficient alternatives, allowing planners to compare trade-offs between efficiency and equity and to select context-sensitive design strategies.

2.5 Artisoc Cloud Platform and Reproducibility

ElderSim was developed and implemented on Artisoc Cloud, a cloud-based agent-based modeling (ABM) platform designed for simulating complex social and spatial systems. Compared with general-purpose ABM tools, Artisoc Cloud offers three advantages relevant to this study. First, its visual rule configuration and modular architecture facilitate the explicit encoding of behavioral rules, making the Elderly-Oriented Facility Interaction Ruleset (EOFIR) transparent and interpretable rather than embedded in opaque scripts. Second, the platform supports batch simulation and parameter sweeping, enabling efficient coupling between behavioral simulation and genetic algorithm-based optimization. Third, its cloud-based execution allows computationally intensive simulations to be conducted without local hardware constraints, enhancing reproducibility across research environments.

The modeling workflow in this study follows a standardized process: (1) spatial environment and facility attributes are imported as input layers; (2) elderly agents are instantiated with heterogeneous behavioral parameters derived from empirical observation; (3) EOFIR governs agent movement, facility selection, social interaction, and adaptation during simulation; and (4) simulation outputs are exported for performance evaluation and optimization. This transparent workflow enables other researchers to replicate or extend the proposed framework using similar ABM environments.

3 Results and Discussion

The simulation results indicate that the optimized layout improves both activity intensity and spatial equity among elderly users. Compared with the existing configuration, total calorie consumption increased by approximately 14.7%, and the distribution of physical activity became more balanced across age and mobility groups. These improvements were primarily driven by reduced walking distances, improved accessibility to high-demand nodes, and the redistribution of facilities to minimize spatial congestion.

Beyond the numerical improvement, the results suggest that the effectiveness of the optimized layout stems from the interaction between spatial configuration and behavioral rules rather than from specific individual preference values. Although the behavioral parameters were derived from a small qualitative sample (n = 10), slight variations in these weights would primarily affect how frequently facilities are used, rather than fundamentally changing spatial activity patterns such as clustering or congestion. In other words, the model's overall dynamics are driven by rule-based interactions embedded in space, which enhances its structural robustness despite limited empirical input.

Fig. 6: Optimized layout of facilities

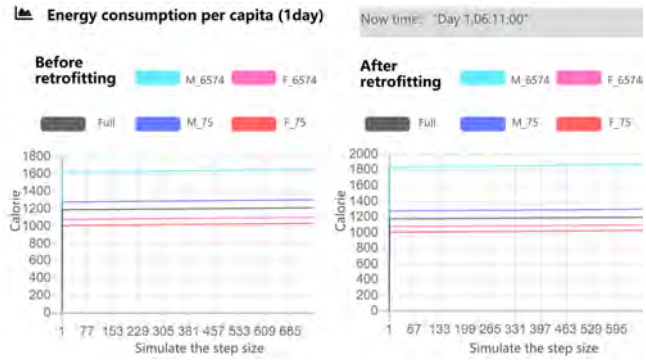

Fig. 7: Comparison of output metrics

Nevertheless, the limited sample size constrains the representativeness of behavioral heterogeneity. Future research will incorporate larger-scale survey data and systematic sensitivity analysis to further evaluate parameter robustness and to enhance the empirical grounding of the model. By linking behavioral simulation with adaptive optimization, ElderSim demonstrates its potential as a transparent and extensible decision-support tool for inclusive community sports planning.

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An Exploratory Investigation of the Experience of Visible Wind Turbines

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Abstract: Wind turbines are normally the largest structures in the landscape, yet little is known about how they are experienced. Most studies of wind turbines focus on their scenic impact and represent them using visualizations. However, scenic judgments of wind turbines by different viewers can be highly variable and require higher-order cognition. In addition, recent research has called into question the validity of using visualizations to assess very large structures, such as wind turbines. This study explores the more intuitive perceptions of wind turbines, specifically the sense of looming and visual prominence of 35 individual turbines and the sense of looming and the feeling of being surrounded by wind farm turbines at nine viewpoints. Changes in scenic quality and fit with the landscape prior to the wind farms are also rated. The results show that the more intuitive perceptions have higher reliability. These perceptions are affected by turbine exposure, proximity, and extent, which can be represented by physical measures such as distance and the arc of the project around a viewpoint.

Keywords: Visual impact, visual prominence, sense of looming, feeling surrounded, exposure, proximity, extent

1 Introduction

Wind turbines are often the tallest structures and wind farms the most extensive developments in a county or state. Such large projects have the potential for several major environmental impacts, yet the one most mentioned by the public is their visual or aesthetic impact (MATTMANN et al. 2016, RAND & HOEN 2017, TSANI et al. 2024). Studies of how wind energy development affects residential property values have found both positive (HOEN, BRUNNER & SCHWEGMAN 2025) and negative (PARSONS & HEINTZELMAN 2022) results. Economic impacts have typically been accounted for in these analyses as either the distance to the nearest turbine whether visible or not (SCHÜTT 2024) or the nearest potentially visible turbine (DONG, LANG & PARENT 2024). The Lawrence Berkeley National Laboratory (LBNL) is investigating the ways wind projects affect home values (BRUNNER et al. 2024) and sought to develop a more sophisticated way of accounting for visual impacts.

Aesthetic impact is a higher-order cognitive assessment and may not be the most reliable explanation of our experience when seeing wind turbines. Many people find wind development in the landscape to be acceptable and even interesting and beautiful, while others find it to be unacceptable. KIRCHHOFF et al. (2022) have even proposed that many people respond to questions about wind turbines' visual impact as a moral judgment rather than as an aesthetic one as traditionally defined. With such divided judgments among the public, using a mean value may not be a satisfying way to gauge the public's reaction. It seems desirable to identify ways to describing experiences of wind turbines and wind farms that are more widely shared.

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A further problem has been how wind turbines have been represented to research participants, where the quality of simulations is often poor and the representations of turbines are abstract or unrealistic (HEVIA-KOCH & LADENBURG 2019). Research has found that even photorealistic simulations of large structures do not adequately capture the experience compared to viewing them in situ (PALMER & SULLIVAN 2020, TAKACS & GOULDEN 2019). For instance, simulations in VIAs are normally static and determine the viewer's focus with a limited angle of view, while viewers in situ choose their point of focus, looking around at turbines and other elements that are moving in the landscape. However, only a very few studies have been conducted in the field because of the difficulty of transporting many viewers to many diverse viewpoints. The major exception is a study by SULLIVAN et al. (2012), but they only evaluated turbines when they were fully visible.

It was in this spirit that LBNL conducted an exploratory study to determine how we experience views of wind turbines and wind farms. It investigated the experience of wind turbine *visual prominence* and *sense of looming*, and wind farm *sense of looming* and *feeling of being surrounded*, as well as more traditional ratings of *change in scenic quality* and *fit with prior landscape character*. The reliability of these ratings is tested, and their relationships to common metrics describing the views of specific turbines and farms calculated.

2 Methods

A diverse team of 3 men and 4 women representing each decade from their 20s through 70s conducted the observations in the field. Their professions included a biologist, two landscape architects, a mathematician, an economist, and two artists. They were given a 2-hour training session that included an illustrated training manual and worksheets for recording observations in the field. The wind farms they observed were located in the Tug Hill (43.79, -75.58) and Central (42.99, -75.76) regions in New York State, as shown in the Appendix B maps. Data about wind turbines and wind farms was obtained from the U.S. Wind Turbine Database (USWTDB) (HOEN et al. 2018). The identification of visible turbines in the USWTDB was accomplished using a procedure described by PALMER (2025).

Observations were conducted at 9 viewpoints, an average of 2 km apart, on July 20 and 21, 2023, during good visibility conditions. The two types of observations were made: 35 individual turbines and the wind farms surrounding the viewpoint. Photographs from four of the locations showing turbines at different distances and landscape settings are shown in in the Appendix B maps. Three new experiential variables, thought to be more instinctive than scenic judgements, are evaluated.

- **Visual prominence** of turbines was studied in the field by SULLIVAN et al. (2012).
- **Sense of looming** for turbines and wind farms was studied by BLAU et al. (2009). It can refer to the instinctive reaction to the vertical, 'over-the-shoulder' presence of a physical object, suggesting an impending threatening feeling (RISKIND et al. 2012) and often triggered by rapid motion toward the observer (THIEU et al. 2024).
- **Feeling of being surrounded** horizontally by wind turbines is identified in interview studies (DUNLAP 2017, LADENBURG et al. 2013), and is noted as a cumulative impact concern (NATURESCOT 2021). However, it has not been the focus of empirical investigations.

These variables are measured from low to high using 7-point rating scales, as shown in Appendix A. Two ratings of visual impact, from −7 to +7, are also obtained. The analyses used the mean rating from the 7 observers.

- **Change in scenic quality** perceived by the public and how to assess its severity has been studied at sites of proposed wind farms by PALMER (2015). The single scale approach is typical of public surveys (LADENBURG & DAHLGAARD 2012).
- **Fit with prior landscape character** can change a landscape's sense of place **(**GOUDRIAAN et al. 2023). BUTLER & WÄRNBÄCK (2019) review how these enormous structures can change the landscape.

Fig. 1: Photographs from different observation locations with turbines in the immediate, near, mid and far distances that also represent the range of landscape settings

In addition, several physical characteristics were recorded. For individual turbines this included exposure (Fig. 2) and perceptually defined distance zones (US FOREST SERVICE 1995). The USWTDB provided data on turbine dimensions and location so the distance to the viewer could be calculated. Observations of wind farms included counting the number of turbines by distance zone and exposure within eight 45° wedges beginning at magnetic north. The observation ended by rating the importance of 10 perceptions describing their experience of the turbines in the landscape. All ratings and observations were done independently.

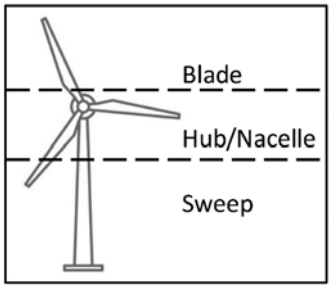

Fig. 2:
Turbine exposure

3 Results

3.1 Reliability

Reliability is measured using the intraclass correlation coefficient (ICC (2, k)) (PALMER & HOFFMAN 2001). The reliability of the three instinctive variables for both wind turbines and farms is excellent, whereas it is only fair for the two wind farm impact variables that require a higher-order cognitive judgment. The reliability of counting visible turbines and wedges with turbines is excellent.

Table 1: Intraclass correlation for the group's rating reliability

		95% C.I.	
Wind Turbine Rating Scales	**ICC (2, k)**	**Lower**	**Upper**
Visual Prominence	0.935	0.881	0.966
Sense of Looming	0.913	0.843	0.953
Wind Farm Rating Scales			
Sense of Looming	0.886	0.722	0.970
Feeling Being Surrounded	0.808	0.534	0.948
Scenic Quality Change	0.409	0.082	0.811
Wind Farm Fit with Landscape Character	0.562	0.086	0.873
Wind Farm Observation			
Count of Visible Turbines	0.998	0.994	0.999
Wedges with Visible Turbines	0.975	0.957	0.987

3.2 Wind Turbines

There is a modest relationship between distance and mean visual prominence (r = -0.471). However, the effect of distance on visual prominence is strongly influenced by the turbine's exposure: sweep (r = -0.749), nacelle (r = -0.333) and blade (r = -0.526). The relationship between distance and sense of looming is also modest (r = -0.419) and the turbine's exposure strongly influences this relationship as well: sweep (r = -0.438), nacelle (r = -0.701) and blade (r = -0.604). These relationships are as shown in Figure 3.

Visual prominence and sense of looming are highly correlated (r = 0.820), and the correlation remains high for different exposures (r values of -0.842, -0.652, and -0.919). This suggests that they may be slightly different expressions of the same fundamental experience.

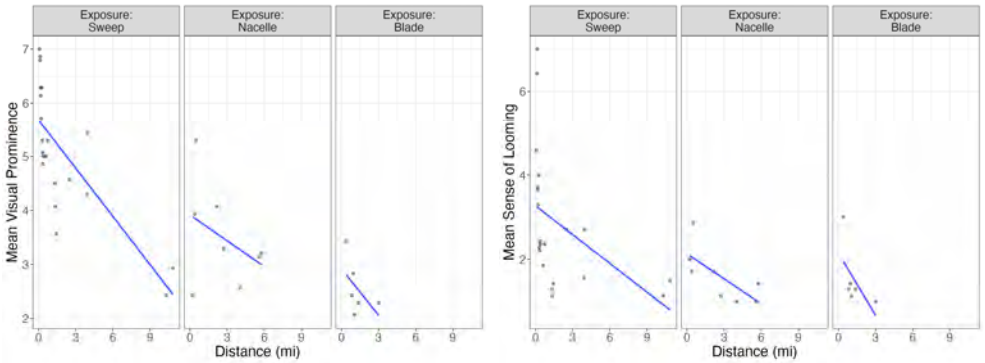

Fig. 3: The relationship between distance and mean visual prominence on the left and mean sense of looming on the right for three turbine exposures

3.3 Wind Farms

The relationship between feeling surrounded and sense of looming associated with the wind farm is weak (r = -0.189), suggesting they are largely independent.

The correlations between the four wind farm experience rating scales and number of turbines and wedges, across all distances and in just the immediate and near perceived distance zones, are reported in Table 2. The relationship with sense of looming is trivial, except between the number of turbines in the immediate and near distance zones where it is still small. On the other hand, the relationship with the feeling of being surrounded is strong, particularly for the number of wedges, and this becomes stronger if only the turbines in the immediate and near distance zones are considered. There is also a strong negative relationship between scenic quality change and the number of turbines, and a moderate positive relationship between the wind farm's fit with landscape character and the number of wedges.

Table 2: Correlation of wind farm ratings with number of turbines or wedges by distance

	All Distances		Immediate & Near	
Wind Farm Mean Rating	**Turbines**	**Wedges**	**Turbines**	**Wedges**
Sense of Looming	-0.070	0.700	0.233	-0.131
Feeling Being Surrounded	0.729	0.874	0.625	0.920
Scenic Quality Change	-0.625	-0.006	-0.266	-0.314
Wind Farm Fit with Landscape Character	-0.187	0.416	0.058	0.166

3.4 Factors Affecting Experience

After completing the turbine and farm observations at a viewpoint, the observers reflected on their overall experience of the wind turbines and landscape and indicated the importance of 10 factors describing their experience at that location. Table 3 lists these factors and the percentage of time their rated importance was low, medium, or high. Perhaps most important is that there is substantial variation in their rated importance, and all factors were judged important at least some of the time.

Table 3: Importance of factors influencing wind farm experience at nine viewpoints

Factors Affecting Experience	Times Rated (%)		
	Low	Medium	High
Distance to nearest visible turbine nacelle	10.1	27.5	62.3
Closeness to some turbines	14.5	27.5	58.0
Shape contrasts with existing character	14.5	29.0	56.5
Wind turbines become the focus of attention	6.0	43.3	50.7
Size of turbines is out of scale with landscape	24.6	31.9	43.5
Density of turbines in the far view	36.4	24.2	39.4
Sense of being surrounded by turbines	25.0	36.8	38.2
Sense that a turbine is looming over me	37.7	26.1	36.2
Landscape changed to more industrial character	23.2	50.7	26.1
Turbines get in the way of the view	56.5	29.0	14.5

Note: There are 63 ratings for each factor (i. e., 7 observers at 9 sites).

Table 4: Varimax rotated principal component loadings of factors affecting wind farm experience

Factors Affecting Experience	Principal Components			Uniqueness
	Proximity	Appearance	Extent	
Distance to nearest visible turbine nacelle	0.870			0.217
Closeness to some turbines	0.839			0.223
Sense that a turbine is looming over me	0.834			0.295
Wind turbines become the focus of attention	0.461	0.536		0.384
Turbine size is out of scale with landscape		0.876		0.202
Shape contrasts with existing character		0.766		0.341
Turbines get in the way of the view		0.702		0.432
Landscape change to more industrial character		0.408	0.604	0.465
Sense of being surrounded by turbines			0.922	0.128
Density of turbines in the far view			0.864	0.214
Percent of variance explained	24.7	24.2	22.1	

Note: KMO MSA = 0.525, Bartlett's Test $\chi^2 = 353.9$ $df = 45$, $p < .001$.

A polychoric correlation matrix from the importance ratings is used for the varimax rotated ordinal principal component analysis (PCA) reported in Table 4 (JASP TEAM 2025). There appear to be three different principal components that explain 71% of the variance. Proximity refers to how close the viewer is to the wind turbines, the sense of looming, and the turbines becoming the focus of attention. Appearance also concerns the turbines becoming the focus of attention as well as their contrast with the landscape. Extent relates to turbine density and the sense of being surrounded. The uniqueness is a measure of the variance for a perception not explained by these three principal components; the lower the value the greater the factor's variance is explained by these three factors.

4 Discussion and Conclusions

This study proposed three new variables to describe the more intuitive experience of wind turbines. Ratings of all three proved highly reliable, more so than ratings of traditional measures of scenic impact and fit with the landscape. The sense of looming and visual prominence of turbines are highly correlated, suggesting they may be different aspects of the same experience. They are both moderately correlated with distance, and this relationship is strengthened by consideration of turbine exposure. The feeling of being surrounded by a wind farm's turbines is strongly correlated with the number of turbines, and particularly with the number of wedges containing turbines. In contrast, the relationship of number of turbines or wedges to sense of looming is poor. It may have been a poor choice to evaluate the sense of looming in relation to the whole wind farm, and a wind farm's dominance in the landscape may be a better way to describe the potential experience.

The field observations at each wind farm concluded with reflective ratings of how important ten possible factors affected the experience. A PCA analysis identified three factors – Proximity, Appearance, and Extent – each explaining over 20% of the variance. These factors would appear to relate the physical dimensions of distance between the viewer and the turbines, turbine exposure, and wind farm extent which were found to be effective in explaining the three intuitive experiences investigated here.

This study was a preliminary exploration to test whether it was possible to reliably measure these more basic intuitive experiences of wind turbines. It has been successful in that objective. However, additional variables describing the experience of wind turbines could also be explored, such as the circumstances that explain wind farm dominance in a landscape or how they change the sense of tranquility (WARTMANN et al. 2019).

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Appendix A: Description of the Rating Scales

Sense of Looming. Rate the extent of your sense that one or more wind turbines is looming or towering over you. It may be related to the need to tip your head back to see all the turbine or it may be its movement in your peripheral vision. It may be a feeling of being in the presence of the turbine rather than it "being out there." It may be accompanied by an uncomfortable feeling, even if you are not looking at the turbine – e. g., it "feels" like something is looking over your shoulder.

Rating	Sense of Looming Description
1	No looming – the turbine is just a spatial element.
3	Weak looming – may need to look up to see the whole turbine.
5	Looming – may need to look up to see the nacelle.
7	Strong looming – perhaps a visceral feeling of the turbine's presence.

Feel Being Surrounded. Rate the extent of your feeling that you are surrounded by wind turbines. This may result from a feeling of being enclosed by turbines. Or maybe it is a feeling that they are blocking or interfering with all the views. It is particularly important that you try and describe why you feel this way, since there is no narrative description for this scale. What contributes to different levels of feeling surrounded?

Rating	Being Surrounded Description
1	Not surrounded.
3	Weakly surrounded.
5	Surrounded.
7	Strongly surrounded.

Visual Prominence. How noticeable is the turbine to the observer? The following table describes different levels of a turbine's visual prominence. Even though there may be a line-of-sight to part of the turbine (i. e., it is in the viewshed), if you are not able to see it, then the evaluation would be Level 1 Not visible. Turbines that are difficult to see are at visual prominence Levels 2 or 3. Turbines are easily seen at Levels 4 or 5. Turbines that draw the viewer's attention are Levels 6 or 7.

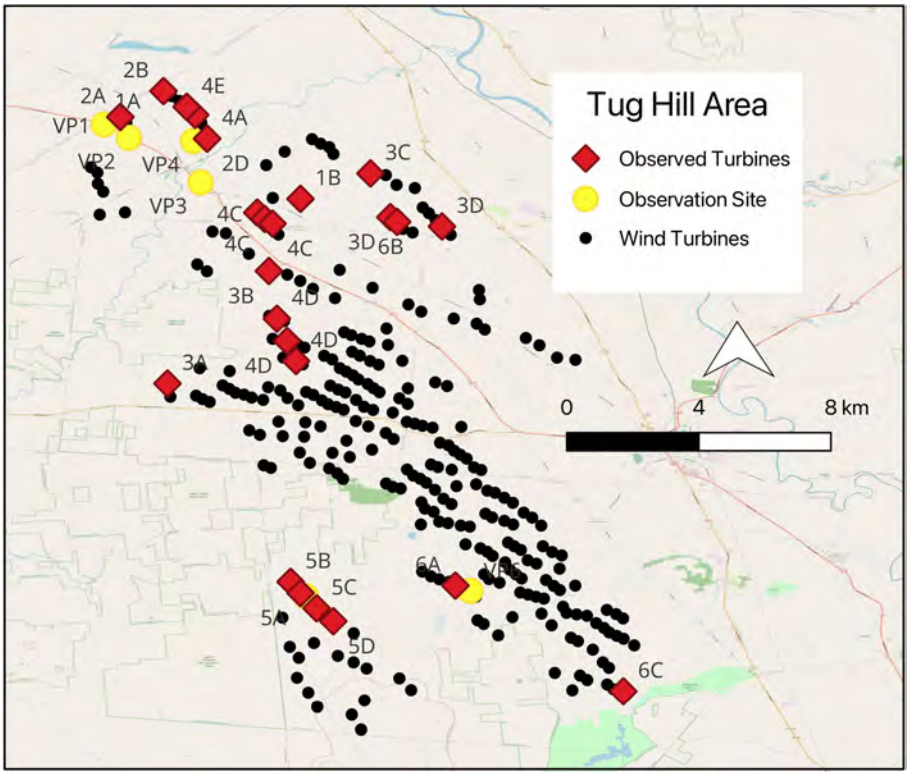
Rating	Visual Prominence Description
1	Not visible, even though there may be a line-of-sight to some part of the turbine.
2	Near the extreme limit of visibility. Would not be seen unless a person was looking for it. Can only be seen after looking at it closely for an extended period of time.
3	Very small and/or faint, but when the observer is scanning the horizon or looking more closely at an area, can be detected without extended viewing. It could sometimes be noticed by a casual observer; however, most people would not notice it without some active looking.
4	Can be easily detected after a brief look and would be visible to most casual observers, but without sufficient size or contrast to compete with major landscape/seascape elements.
5	Is obvious and with sufficient size or contrast to compete with other features, but insufficient to strongly attract visual attention and insufficient size to occupy most of the observer's visual field.
6	Not of large size, but contrasts with the surrounding features so strongly that it draws and holds viewer attention immediately. It interferes noticeably with views of nearby features.
7	Strong visual contrasts. Large apparent size dominates most of the visual field, and views of it cannot be avoided except by turning the head more than 45 degrees from a direct view. Major focal point that detracts noticeably from views of other Features.

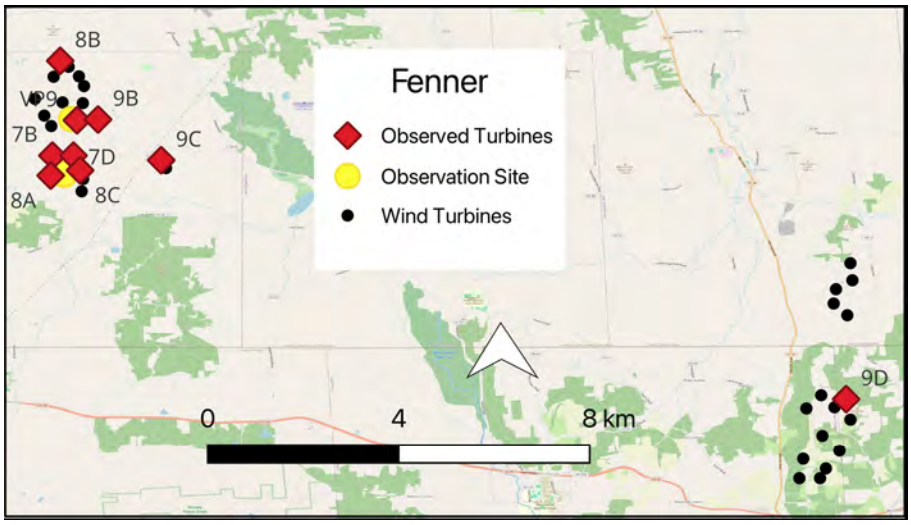
Wind Farm Fit with Prior Landscape. All landscapes have character – it is neither good nor bad, it just is. However, landscapes are also constantly changing, sometimes due to natural causes and other times human causes. If a change between the landscape prior and after introducing wind turbines is Not Apparent, rate it 0. If the change fits Very Well and enhances the prior landscape character it would be rated +7 with other positive fit changes between +1 and +7. If the change fits Very Poorly and changes the landscape character beyond recognition, it would be rated –7 other negative changes in the fit between –1 and –7.

Scenic Quality Change. Consider the scenic quality of the prior and existing landscape views. How would you rate the change in scenic quality attributable to the wind turbines as experienced from this location?

Appendix B: Study Area Maps

These maps are of the study area wind farms. Observation sites are numbered VP1, VP2, etc. and individually observed turbines by their observation number and order 1A, 1B, etc.




Fenner
Observed Turbines
Observation Site
Wind Turbines
8B
9B
7B
9C
7D
8A
8C
9D
0
4
8 km

Reciprocal Action to Responsive Design: A Global-to-Local-to-Global (GLG) Geodesign for Climate Mitigation Workshop

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Abstract: Across disciplines, students are demanded to respond to climate change. The Global-to-Local-to-Global (GLG) Geodesign Project provides a systemic framework for mitigation as multi-scalar cooperation, offering a valuable case for education in environmental planning and design. This session presents how the GLG Project advances teaching climate change mitigation through Geodesign: unpacking fundamentals of geospatial modeling, linking land-based spatial practices to analysis-design iteration loops, and fostering new capacity for multi-scalar, responsive design.

Keywords: Geodesign, climate mitigation, design pedagogy

1 Introduction

The current climate crisis requires fundamental adjustments to human settlements worldwide, demanding that landscape architects and urban planners continuously reimagine land and landscapes. This reimagining is not a single act but a dynamic process of reciprocity: local actions impact global climate, which in turn forces new local adaptations. To effectively navigate this feedback loop, future practitioners must learn and adopt a broad range of techniques for modeling the projective impacts of climate change to future land use and urbanization based on a multitude of geospatial and design inputs. The core challenge for design education, therefore, is to move beyond teaching tools by unpacking the multivariate geospatial modeling of these diverse inputs, better linking land-based spatial practices to iteration across temporal and jurisdictional scales, and ultimately fostering a new capacity for multi-scalar, responsive design.

The International Geodesign Collaboration's (IGC) Global-to-Local-to-Global (GLG) project provides a systemic design and planning framework to support climate change mitigation as a problem of multi-scalar cooperation. It operates from the critical understanding that climate change is a "global existential phenomenon, no nation can control its own climate, and if climate mitigation is to succeed, all nations must act in collaboration." (ERVIN & STEINITZ 2025) This multi-jurisdictional, multi-scalar problem has motivated the creation of a digital Decision Support System (DSS) (STEINITZ 2012) and a series of workshops around the world to simulate the impact of local decisions on global climate change and future mitigation capabilities.

While the GLG Project addresses issues of coordination for climate action, climate mitigation is fundamentally a problem of land-based planning and environmental design. Present-day commitments, such as wetland conservation, impact future carbon management. They also necessitate other actions, like expanding renewable energy, which places new demands on

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land. This reciprocity – global climate change, to local action, to global climate impacts – reflects the continued reimagining of land and landscapes that will shape the careers of coming generations of landscape architects, urban designers, and spatial planners.

As such, the GLG Project's approach to modeling climate actions and outcomes provides a valuable case for teaching responsive, multi-scalar spatial practice to environmental designers and planners in the climate change era. Working from global-to-local-to-global, the GLG framework reinforces the following key ideas in climate mitigation practice across scales:

1) **Geospatial modeling fundamentals:** Understanding how a set of decisions that implicate spatial action translate to multivariate geospatial modeling of climate impacts to land cover, land use, and urbanization.
2) **Analysis-design feedback loops:** The critical importance of cycling between analysis and design rather than treating them as separate phases.
3) **Responsiveness to change over time:** The need to design to longer time horizons – such as 2050 – and the importance of revising a design in iteration between phases of analysis such that the design adapts to new challenges or capabilities of changing conditions over time.
4) **Coordinated efforts for practice in changing future conditions:** Recognition that large-scale coordinated interventions implemented now fundamentally alter the design conditions and possibilities available in the future.

These ideas emerged from a September 2025 workshop on Global-to-Local-to-Global (GLG) Geodesign for Climate Mitigation at Harvard. In evolution of a previous workshop in January of the same year, the September workshop expanded in diversity of participants from students of landscape architecture to programs in urban planning, policy, public health, and more. It engaged students in traveling design studios sited around the world to align takeaways with pedagogical questions of design for climate mitigation.

Across disciplines, students are demanded to respond to climate change. Under these shifting social and technological conditions – from global climate cooperation to the acceleration of geospatial modeling under big data, machine learning, and artificial intelligence – the GLG Project offers a valuable framework. It educates designers on the causes and effects of their actions, preparing them for anticipatory practices that mitigate future climate change, rather than merely adapt to its outcomes.

2 Design Workshop

2.1 Setup

The September 2025 Global-to-Local-to-Global (GLG) Geodesign for Climate Mitigation Workshop at Harvard GSD advanced the GLG design and planning framework through the method of a multi-day participatory design workshop, beginning with a one-hour introductory lecture from Professor Carl Steinitz, followed by a day-long hands-on session. Partici-

pants from across the Harvard/MIT consortium and guests from Clark University were assigned to work in groups of three to represent one of 12 mid-scale jurisdictions worldwide.[1] These areas represented regional entities where climate governance could be exercised – primarily at the provincial, municipal, county or state level.

Seven of the 12 study areas were sites of Fall 2025 option studio courses at the Graduate School of Design, providing an opportunity for participants in option studios to use workshop results to spur design considerations for future conditions. This positioned the application of the GLG System to address a fundamental question for design studios: "For what time-frame should you be designing? If you plant a forest now, will the climate region have changed by 2050?" (STEINITZ 2012).

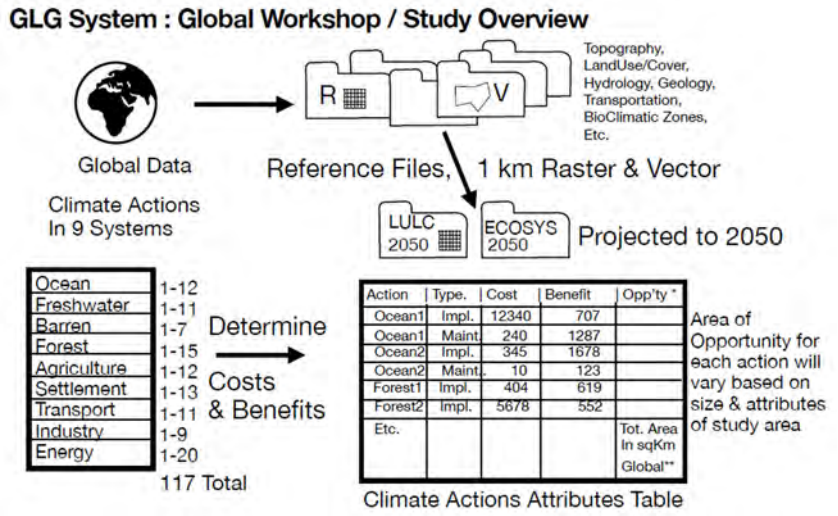

Fig. 1: Conceptual diagram outlining underlying data, climate actions in 9 systems, and climate action attribute table for the standard GLG Decision Support System

The GLG Decision Support System operates by aligning a set of possible Climate Actions across nine global "systems" modeled from a set of geospatial vector and raster reference files representing features where actions may occur or are impacted by action/inaction. These actions are assigned attributes for impact over time using 'Gantt Charts' that require project status (implementation and management or management only), start date (year), and percent feasible (1%-100%).

Following the assignment of climate action attributes, a nine-system global model predicts conditions for 2050. The model assumes that, as long as unitary values referring both to emissions reduction by km^2 and cost by km^2 are known, for any area deemed suitable for a project type, its emissions reduction will amount to the product of its area (in km^2) by the

[1] The full list of assigned jurisdictions includes: *Chicago, Illinois (USA); *Los Angeles, California (USA), *Santa Barbara County, California (USA), *Napa County, California (USA); *Geneva, Switzerland; *Valencia, Spain; *Kyoto, Japan; Beijing, China; Goa State, India; Lima, Peru; Rivers State, Nigeria; Jakarta, Indonesia. (*) indicates Fall 2025 Option Studio site.

defined percent feasibility and its unitary emissions reduction value. A similar reasoning can be produced to estimate cost and whenever projects overlap, cumulative values must be calculated. This projective multivariate modeling considers climate actions as spatially-explicit mitigation projects, and the assignment of attributes by users as representative of simplified decision-making performed by planners or policy makers within long-term climate planning processes.

For the design workshop, participants were asked to take on the role of long-range central planners for their assigned jurisdiction to make decisions on a set of 117 pre-defined GLG Climate Actions representing place-specific and time-based regional climate mitigation projects. As a means of simplifying considerations of actual democratic processes and barriers to land-based climate mitigation, participants were asked to consider (1) political, social, or financial "readiness" of a given jurisdiction for implementing climate actions, and (2) to keep total costs of their decisions within 5-10% of the estimated GDP for their study area, to reflect a hypothetical maximum spending available.

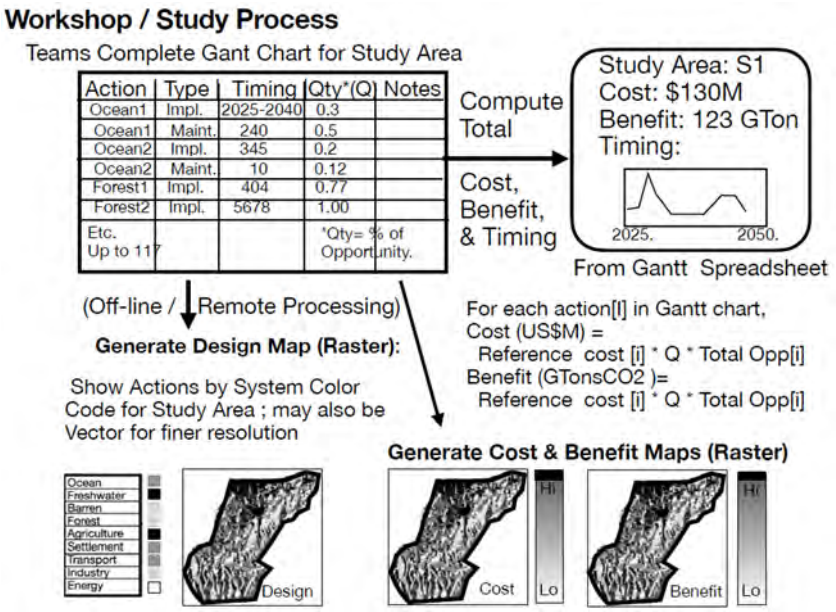

Fig. 2: Diagrams outlining workshop study process undertaken by participant groups, assigning climate action attributes in 'Gantt Charts,' modeling estimated costs over time, and contributing to the generation of 2050 design and cost/benefit maps

To aid in the decision-making process, each group was given a multi-page PDF summary generated by Perplexity AI containing relevant climate-related actions, regulations, organizations, and priorities for their respective mid-scale jurisdiction. Using these resources, they were asked to make decisions regarding climate action attributes using 'Gantt Charts' in Microsoft Excel that modeled time-based costs in real time according to land area and estimated regional GDP. Due to the time constraints of a one-day workshop, participants worked to quickly make educated decisions on as many of the 117 GLG Climate Actions as possible using this available information – aiming to contribute to a simulation of the global scale

impacts of a large number of land-based climate mitigation projects, rather than drill deeply into the feasibility of individual actions.

These ‘Gantt Charts’ became the input for modeling how decisions interact within dynamic global climate models to generate an expert ‘Design Map’ that informs more targeted design investigations. At the same time, students were asked to create their own design diagrams to illustrate: (1) their immediate climate mitigation strategies as they would materialize within their study area boundaries, and (2) the projected implications for their study area assuming full implementation and management of their climate plan by 2050.

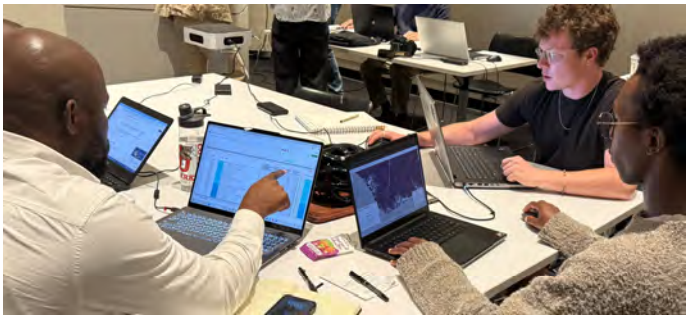

Fig. 3: Participants making decisions on climate actions by inputting attributes related to project type, timing, and cost into ‘Gantt Charts’ (Credit: Rivers State, Nigeria, Team – Pacifique Mandibi, Grant Stokes, Kalu Okigwe, and Toby Matus-Bond)

Breaking down decisions for global climate models into actions with temporal and spatial parameters is critical for teaching fundamental principles of multivariate geospatial modeling for climate change mitigation in a collaborative manner, outside of GIS software. Associating actions with costs then asking students to diagram the spatial implications intuitively in geographic space, is critical for helping students connect geospatial modeling with environmental design and planning.

The workshop culminated in a final presentation where teams were asked to show diagrams of modifications to the base land cover/land use maps for their study areas, and slides featuring each team's ‘Gantt Chart’ and systems cost graph. After sets of three strategically paired groups, workshop facilitators asked teams to display either their diagrams or systems cost graphs simultaneously for comparative analysis of readiness, implementation costs over time, and predicted carbon emissions mitigation. They were then asked to speculate on how they would revise their ‘Gantt Charts’ in response to modeled global climate impacts or projected costs – imagining the process as an iteration of design-and-response.

2.2 Results

The workshop resulted in concrete takeaways in understanding the comparative readiness of mid-scale jurisdictions for climate actions, the links between time and cost, and the importance of iteration between modeling and design across scales to move past “unique and one-off” interventions to coordinated efforts that “add up” to create systemic change.

As an example, a valuable case study emerged in comparing Geneva, Switzerland and Rivers State, Nigeria. Geneva presented minimal land use change but exceptionally high implementation costs, yet possessed strong capacity to bear these expenses – a high-cost, high-capacity scenario where financial resources align with implementation needs. In contrast, Rivers State demonstrated extensive projected land use changes with significant landscape impacts and substantially lower implementation costs, but considerably less capacity to bear even these reduced expenses – creating a low-cost, low-capacity paradox. This comparison illuminated a fundamental challenge: the regions with the greatest need for landscape-scale interventions and lowest costs often lack the financial infrastructure to execute these critical programs.

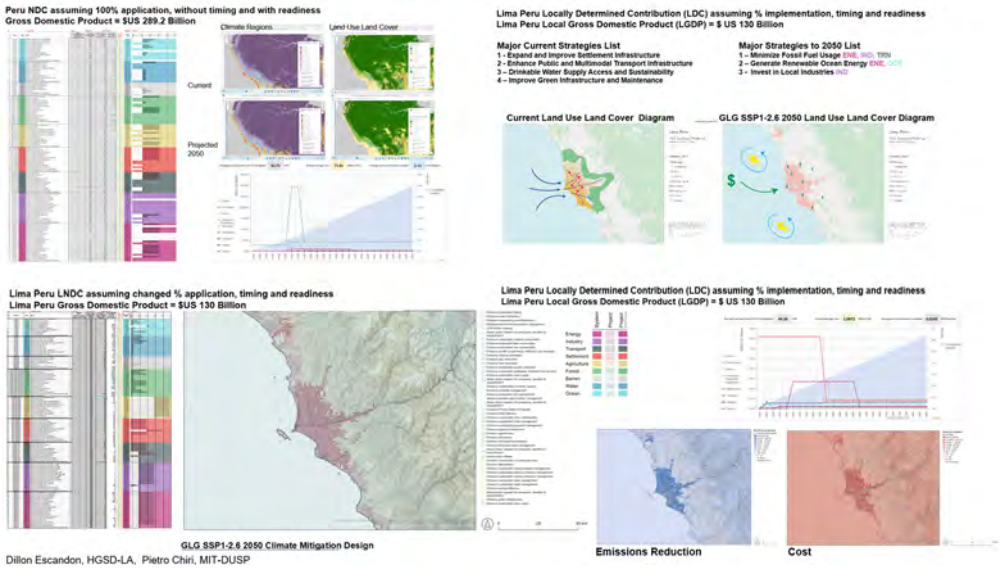

Fig. 4: Results of the GLG Design Workshop from Lima, Peru. (top-left) Peru NDC assuming 100% application; (top-right) Lima, Peru Locally Determined Contribution, Major Current Strategies and Strategies for 2050, and diagrams; (bottom-left) Lima, Peru LNDC with climate action 'Gantt Chart' and 'Design Map'; (bottom-right) Lima, Peru, Locally Determined Contribution assuming % implementation estimated Benefits (Emissions Reduction) and estimated Cost (Credit: Lima Workshop Team – Dillon Escandon and Pietro Sandro Chiri Zapata)

Santa Barbara served as an additional case study, connecting the GLG framework to ongoing work at Harvard GSD's Department of Landscape Architecture. The project demonstrated how spreadsheet-based decisions integrate with conceptual diagramming and geospatial analysis to address anticipated urbanization and landscape change. The team identified three major strategies for renewable energy transition: solar photovoltaic systems, offshore wind energy, and sustainable agricultural practice – facilitating energy transition while remaining sensitive to Mediterranean climate conditions where wildfire events are intensifying.

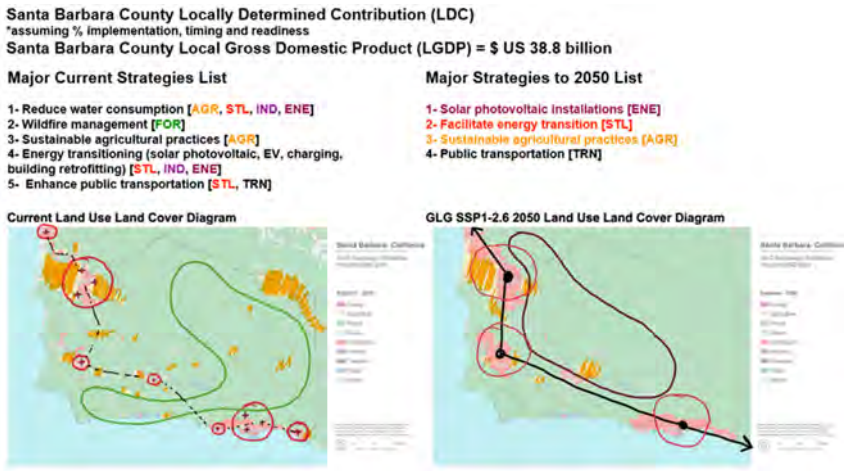

Fig. 5: Major current strategies, major strategies for 2050, and diagrams indicating design strategies for each period for Santa Barbara County

Fig. 6: The modeled expert 'Design Map' for Santa Barbara, considering actions, implementation, and costs selected by group participants (Credit: Santa Barbara Team – Eva Gildea, Jake Geitner, and Rifaa Asna Tajani)

This process prepared students to align regional and global climate priorities with site-scale design realities using geospatial modeling and evidence-based speculation. The outcomes are not intended to prescribe a resolved design for each project within the study area. Rather they act to bridge the strategic priorities held by governing bodies to the land that will be needed to achieve climate mitigation goals, not just locally but as a collective global effort. This aids in resolving a scalar challenge in climate mitigation by spreading implementation rationally across landscapes and jurisdictions that are best suited for certain types of projects based on readiness and costs, fostering global cooperation in climate action.

3 Discussion

The results of the GLG design workshop reinforced the pedagogical goals of teaching geospatial modeling fundamentals, analysis-design feedback loops, responsiveness to changing conditions over time, and coordination of efforts across jurisdictions for multi-scalar approaches to long-term climate mitigation planning. While some of these goals were implicit in the workshop premise and setup, they were made explicit through the process of working with participant groups during the workshop and in reflection on strengths and weaknesses after the workshop's conclusion.

Fig. 7: Student presentations comparing 3 mid-scale jurisdictions side-by-side: Rivers State, Nigeria; Goa State, India; and Jakarta, Indonesia (Credit: Pacifique Mandibi, Grant Stokes, Kalu Okigwe, and Toby Matus-Bond)

The process revealed certain limitations of addressing such a large challenge in a day-and-a-half workshop. With 117 Climate Actions for teams to evaluate, participants had to move quickly to make judgements about project "readiness" and timelines for implementation with varying levels of sectoral or geographic expertise for the climate mitigation decisions within their assigned jurisdiction.

Additionally, the computational demands of modeling the impacts of each group's 117 climate actions to a 1km global-coverage raster representing the nine "systems" severely hindered the output of 'Design Maps' during the time frame of the workshop. The GLG workshop team only had two hours to model results based on submitted 'Gantt Charts' during the workshop, so groups relied heavily on their design diagrams and projected cost estimates aiming between 5-10% local GDP for their final presentation.

These issues could be addressed in future workshops by: (1) giving groups ample time in advance to read supplementary material and research action timing, and (2) providing larger windows between 'Gantt Chart' submission and discussion to allow complete modeling of 'Design Maps' for 2050. Both issues may benefit from increasing the application of AI in the workshop process – in helping participants access information by extending resources like the regionally specific climate priority PDFs produced by Perplexity AI, and in reducing compute time for multivariate geospatial modeling of climate action impacts.

Acknowledging these limitations, it is worth noting the value of the workshop in providing a means to engage with multi-scalar, multi-jurisdictional issues of climate action as a design question, without requiring the resolution of all complexities of global cooperation and implementation as a pre-condition. “There is a class of problem …looking into the future…that will always have complexity and uncertainty. The more detail, the more wrong it will be perceived.” (Steinitz 2012). Of course, resolving each climate action in a specific place will necessarily require localized expertise, navigation through political realities, comparative readiness, and considerations of equity. Providing a venue to iterate quickly between scalar questions of action and impact can help students contextualize the relationship between global cooperation and local impact as a question of land-based planning and design.

In this manner, the GLG Design Workshop’s simulation of iteration between cause-and-effect relationships underscores the need for environmental designers and planners – who may already think well at local or regional scales – to envision design as collective global climate action. The results of the GLG design workshop demonstrate a unique opportunity to prepare future practitioners to think telescopically from the global to the local as they consider – and reconsider – anticipatory practices that mitigate future climate change.

4 Conclusion

The September 2025 GLG Workshop yielded significant educational outcomes for environmental designers and planners, centered on the following key ideas:

1) **Geospatial analysis as a systematic framework:** The exercise showed how multivariate suitability analysis across a wide-ranging number of climate actions can be "unpacked" by turning variables on/off to understand both the spatial and temporal dimensions of design impacts within broader planning schemes.
2) **Iterative analysis-design cycles revealing compounding effects:** The workshop demonstrated how moving between analysis and design phases allows large-scale interventions to fundamentally alter future design conditions, showing how systematic decision-making creates cascading opportunities.
3) **Cost analysis revealing implementation disparities:** The workshop highlighted significant financial barriers, comparing regions like Geneva (minimal land use change, high costs, strong financial capacity) versus Rivers State, Nigeria (extensive land use change, lower costs, limited financial capacity).
4) **Multidisciplinary collaboration enhancing results:** Teams combining participants with diverse expertise were more effective. Participants with planning and public policy backgrounds brought realistic implementation understanding while designers contributed spatial thinking and visual communication skills.

As the technical workflow continues to advance, particularly in the geospatial modeling required to produce expert ‘Design Maps’, the ideas from this workshop reveal opportunities for the GLG Project to prepare future practitioners for the multi-scalar reality of mitigating climate through design. Future work can focus on unpacking multivariate geospatial modeling – teaching techniques over tools. It can also better link land-based spatial practices to iteration across temporal and jurisdictional scales, ensuring future projects anticipate the impacts of previous decisions and that planning ideas remain fluid among shifting governance realities. Since climate change requires global cooperation, this GLG workshop sets the stage for new pedagogical practices in multi-scalar, responsive design.

Acknowledgements

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Slide Kelly (Design Critic in Landscape Architecture), Lorena Bello Gomez (Design Critic in Landscape Architecture), and Bruce Boucek (Senior GIS and Data Librarian, Frances Loeb Library).

Workshop Participants included:

Gulsah Aygun Orhan, Shreya Bansal, Pang Boonbaichaiyapruck, Sarah Boufkiri, Catherine Cai, Yichao Chen, Yushuo Ding, Dillon Escandon, Marine Gapihan, Gabriel Garon, Jake Geitner, Valentine Geze, Eva Gildea, Javier Irigaray, Spurty Kamath, Tea Kim, Ayşe Koyun, Amanda Kusumawardani, Naning Li, Angela Lim, Zeliang Lyu, Pacifique Madibi, Lio Mathurin, Tobias Matus-Bond, Sophia Millay, Mary Monjazab, Oliver Oglesby, Kalu Okigwe, Clarisza Runtung, Pietro Sandro Chiri Zapata, Grant Stokes, Rifaa Tajani, Matt Thibodeau, Savalee Tikle, Charlotte Williams, Siyi Wu, Anna Zaremba, and Sophia Zhang.

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STEINITZ, C. (2012), A Framework for Geodesign: Changing Geography by Design. ESRI Press, Redlands, CA.

Use of Artificial Intelligence (AI)

PERPLEXITY AI (2025), [Large language model]. https://www.perplexity.ai/

Used to generate summary National Determined Contribution (NDC) PDF documents for each mid-scale jurisdiction assigned in workshop. Perplexity AI was queried about relevant (sub-national) local and contextual climate-related actions, regulations, organizations, priorities, etc. to generate a multi-page PDF summarizing each jurisdiction's NDC's alignment with GLG climate projects.

ANTHROPIC (2025), Claude 4 (v. Sonnet). [Large language model]. https://claude.ai/

Used for transcription of voice notes from lead author outlining key takeaways following workshop conclusion. Voice note transcripts were uploaded from the Voice Memos iOS app to Claude 4 Sonnet within the Harvard University Information Technology (HUIT) AI Sandbox secure environment. Claude was asked to "Please edit voice note for grammar and clarity and clean it up into a summary of bullet points."

GOOGLE (2025), Gemini Pro (v. 2.5). [Large language model]. https://gemini.google.com/

Used to edit extended abstract and full paper submission for grammar and clarity within the HUIT AI Sandbox secure environment. Changes were made to flagged passages by hand.

Prototyping an App for Teaching Soundscape Design and Evaluation

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Abstract: The quality of soundscapes is receiving increasing attention in sustainable urban design. However, there is a crucial gap in educating students of the landscape architecture and spatial and urban planning disciplines how to design and evaluate soundscapes. In particular, media are missing to communicate, analyse and assess soundscapes and their changes through urban design measures in an audible way. Our goal was, therefore, to develop a tool to make working with environmental sound more accessible to landscape architecture and planning students. It should translate real-world requirements and concepts into an easy-to-use tool. The paper focuses on the technical development process including identifying user requirements through expert interviews, conducting an interdisciplinary workshop for elaborating a syntax for subsequently developing a prototype, and using and evaluating the prototype in courses with students. The prototyping led to an app based on a modular concept for spatializing in real-time 3D audio data within a visual 3D environment. Insights from first implementations of the prototype as teaching medium show that students liked what they were learning and that the app was helpful for demonstrating the layered structure of sounds and their interactions with the environment. Although students appreciated the contextualization of sounds in a visual 3D model, functions to concentrate on the audio only were missing. Moreover, the app's usability needs to be significantly enhanced through better documentation. Further investigation is required to define what is a suitable level of detail of audiovisual simulations for interactive soundscape design and evaluation. Moreover, investigations should compare the students' soundscape analyses of real sites versus the ones based on the virtual representation.

Keywords: Teaching media, environmental sounds, auralization, 3D visualization, game engine

1 Introduction

The acoustic environment is an important aspect of landscape quality. Environmental noise, in particular from transportation, is recognized as a crucial issue in cities and agglomerations worldwide, annoying people and affecting people's health and well-being as well as biodiversity (CAN et al. 2020, EEA 2025, MURPHY & KING 2022, SCHULTE-FORTKAMP & FIEBIG 2023). Therefore, environmental policies and actions are increasingly enacted that aim at mitigating noise and fostering acoustically pleasant outdoor places (CAN et al. 2020, EEA 2025). However, in practice, effectively designing public urban places to meet the set goals turns out difficult, calling for a better understanding of how urban and landscape planners design healthier acoustic environments (CAN et al. 2020, FRICKER et al. 2024, MURPHY & KING 2022, TARLAO et al. 2023). Raising awareness should already start with the education of the future practitioners, who are responsible for designing respective solutions. Teaching

theory-based audiovisual perception of space, digital reconstruction of acoustic environments, as well as their evaluation and design should be established (BRÜHNE 2023). This paper describes the prototyping of an application designed to help users understand and respond to environmental sounds in urban design.

As the acoustic environment consists of a superposition of several sound events which interact with the physical landscape elements and affect human perception, understanding and simulating it is a complex task (SCHULTE-FORTKAMP & FIEBIG 2023). Traditional quantitative noise assessment approaches based on sound pressure levels fail to provide information on how the quality of the sound is perceived by humans. Hence, more recent approaches are based on the concept of soundscape, which can be considered as the sound environment of a place as perceived, experienced or understood by humans in a context (CAN et al. 2020, SCHULTE-FORTKAMP & FIEBIG 2023). Therefore, the goal was to develop an app for auralizing virtual 3D landscape environments so that students and others who primarily use visual design tools and are not familiar with environmental acoustics can better imagine the concept of a soundscape. Specifically, theoretical principles of soundscape should be illustrated and made tangible, students should be enabled to apply these principles to the design of outdoor places and assess the changes in terms of their perceived acoustic quality. In this way, students should build up competence in dealing with the quality of environmental sounds, sharpen their spatial perception of specific effects such as the acoustics of spatially open or closed landscape situations, and be motivated to include the soundscape in early planning and design phases. To this end, visual and aural 3D data should be combined in a virtual 3D model, as such teaching media are not yet available.

While existing soundscape simulation frameworks often prioritize ecological validity, they typically require advanced acoustic expertise and complex setups, creating significant entry hurdles for students. Therefore, the central novelty of this paper lies at the intersection of technical development and student-centred usability within digital design pedagogy. The focus of this paper is on the technical development process. In section 2, the prototyping process – including the first implementation of the app – is presented. Section 3 provides the results of reflecting on the development process and user feedback, pointing out the prototype's strengths and weaknesses from a lecturer and student perspective. On this basis, suggestions for further enhancements are given in section 4, whereby the current limitations and the trade-offs between usability and ecological validity are critically discussed.

2 Prototyping

Agile methodologies, which focus on user requirements, collaboration, rapid iterative development and continuous improvement, have proven to foster more successful and efficient software development (PALOPAK & HUANG 2024). Therefore, we designed a process that follows agile principles, starting with a user requirement specification to inform the conceptualization of the app. This led to an initial prototype that was iteratively tested and enhanced. Implementing the prototype in courses with students revealed how well the application already functions. In the following, the individual phases are briefly presented.

2.1 User Requirement Specification

First, interviews were conducted with seven experts in the field of acoustics, noise protection, auralization, and soundscape design in practice and teaching. The experts were recruited from a pool of sound specialists and lecturers associated with an academic research centre that promotes knowledge transfer between researchers, industry, and agencies (https://design-plusplus.ethz.ch). In the form of one interviewee and one interviewing person, one hour interviews followed a guideline comprising an entry question on the expertise regarding auralization, and main questions on simulation approaches (required data, formats, infrastructure, time requirements, accuracy needed, possibility of real-time adaptation, required expertise, accessibility, costs) as well as on the intended app (value for soundscape design, how it would be applied, required interfaces, further remarks or thoughts). In the end, the interviewees were thanked and asked whether they would like to receive notice of the publication of results.

Transcripts of the interviews' audio recordings were qualitatively analysed by thematically summarizing the information provided on each question. Themes such as the app's "simplicity/complexity", "realism", "interactivity", "formats", "application situations", and "technical aspects" were derived from going through the transcripts. Then, the statements were assigned to these themes. Aspects mentioned by different experts were regarded more important than those mentioned only once. In this way, user requirements, specific goals and application situations for soundscape simulation were revealed. In particular, simple tools with low complexity were said to be needed to facilitate access for people with limited knowledge of acoustics. The simulation should be realistic enough to give an impression of the basic acoustic atmosphere of a space. For the intended purpose of soundscape design in early planning phases, the experts regarded a realistically perceived soundscape more important than modelling a physically highly accurate soundscape representation. For the latter complex synthesizers can be elaborated (PIEREN et al. 2017), however, they are neither freely available, nor easily implementable. Therefore, an approximation of the soundscape with an interplay of everyday sounds should be simulated. In addition, lecturers described a targeted use of the app for different course modules, namely for demonstrating theoretical aspects, for analysing an existing soundscape by hearing how different sounds behave in open or closed spaces, as well as for designing and evaluating scenarios. For comparison of alternative designs and evaluation of the respective soundscapes, the app should support subjective judgments if the experienced quality of the soundscape at a location is pleasant by reflecting on one's own perception informed by hearing (HOCKS & COMSTOCK 2017). Overall, these results helped to focus the development of the app.

2.2 Syntax and Prototype Development

In a next step, a two-day workshop was conducted for elaborating a syntax of the app and then developing a first prototype that demonstrates what needs to be programmed. The workshop was consulted by a spatial audio expert, who guided the definition of the app's functions and respectively required in- and output parameters for a game engine and a sound mixing tool to translate phenomena such as occlusions into technical effects that are perceived as realistic. Further participants were a programmer, a sound artist, a landscape acoustics designer, and a researcher in 3D landscape visualization. The workshop was conducted in an audiovisual lab, where programming and listening to intermediate results was possible.

Fig. 1: Perimeter of the study sites: Open landscape situation (left) and closed landscape situation (right). The dashed lines indicate the viewing angle of the perspective visualizations provided below (Orthophotos: © geo.admin.ch, Federal Office of Topography swisstopo; Perspective visualizations: Terrain: © Cesium, Cesium World Terrain. Data/Imagery: © Google (2026), Photorealistic 3D Tiles).

For the first workshop day, visual 3D models were prepared in the Unity game engine (UNITY TECHNOLOGIES n. d.) representing areas, which were chosen as study sites for courses (Fig. 1). The first model was a more open landscape of approx. 1 km^2 containing settlements, pastures, trees, a creek and a highway, which is covered in one scenario. The second one was an urban area of approx. 0.5 km^2 with a rather closed situation with dense and high buildings, paved squares with single trees, streets, train tracks, and a river. The Unity models included objects that are sound sources, such as birds, cars, trains, and water objects. Moreover, ambisonic, i. e., 3D sound recordings, of the sites were available to allow plausibility checks of the auralization. These 3D models served targeted discussions on the app's functionalities. Use cases for the app in the planned courses were described and possible technical solutions were elaborated. The participants had also to decide on the priority of a certain function to be implemented considering the importance for supporting teaching and the realizability in the limited time. Specifically, it was determined that occlusion and reflection would be implemented using simplified models, as accurate physical simulations of these phenomena introduce significant algorithmic complexity and computational overhead. This resulted in a concept for programming of a modular tool, which allows to swiftly give an impression how

a 3D environment could sound. Thereby, the user interaction should primarily take place in the visual 3D model by adding and configuring characteristics of objects (i. e., trees, birds, cars etc.) by assigning type, movement, sound files, etc.

The second day started with an initial prototype programmed by the audio expert using Panoramix (IRCAM n. d.), a sound mixing console of IRCAM's Spat Library. It is running inside Max (CYCLING'74 n. d.), which is a real-time graphics development software for multimedia applications. In the following, a Unity interface was programmed to control the mixing tool through Open Sound Control (OSC) messages that convey information on the coordinates of the listener position ("Player"), the landscape elements (game objects: buildings, trees, cars etc.), and assigned sound files chosen from a folder of an audio library (Fig. 2).

Fig. 2: Soundscape Unity Package with a 3D model, a "Player" and "Settings" prefab, the Audio Library plugin, and "Sound Source Audio" component to select audio files and define type (e. g., mono) and source (= track, e. g., mono source 1) in the Panoramix Mixer. The "OSC" script is based on the Make Controller Kit1 C# OSC Library (POIRIER-QUINOT 2019) to send and receive OSC messages for communicating between Unity and Panoramix.

Refining the prototype after the workshop, two Unity components were programmed: (1) "Sound Source Audio" and (2) "Sound Source Generator". "Sound Source Audio" is used to design a soundscape with three types of sources, "Mono", "Stereo", and "Multi" (Fig. 2). Through the component's settings, these sources are assigned to tracks in Panoramix, namely,

16 “Mono”, i.e., single-channel audio sources, e.g., for cars, trains, birds, etc., 8 “Stereo” sources for sounds that are more atmospheric (e.g., field recordings of human voices, footsteps, rain, etc.), and 4 “Multi” sources, which are multichannel ambisonic B-format files.

The “Sound Source Generator” generates wind and water (Fig. 3). The “Wind Generator” can auralize either a single tree or groups of multiple trees (forest), and foliage type and size can be set. Assigning the component to the parent of a group of game objects, a forest size is calculated using the game objects in the parent and creating a wider sound than for a single tree. The “Water Generator” allows to choose a flow type water (river) or a fountain type, to define the size of the water object, and the duration of splashing and breaks for the fountain.

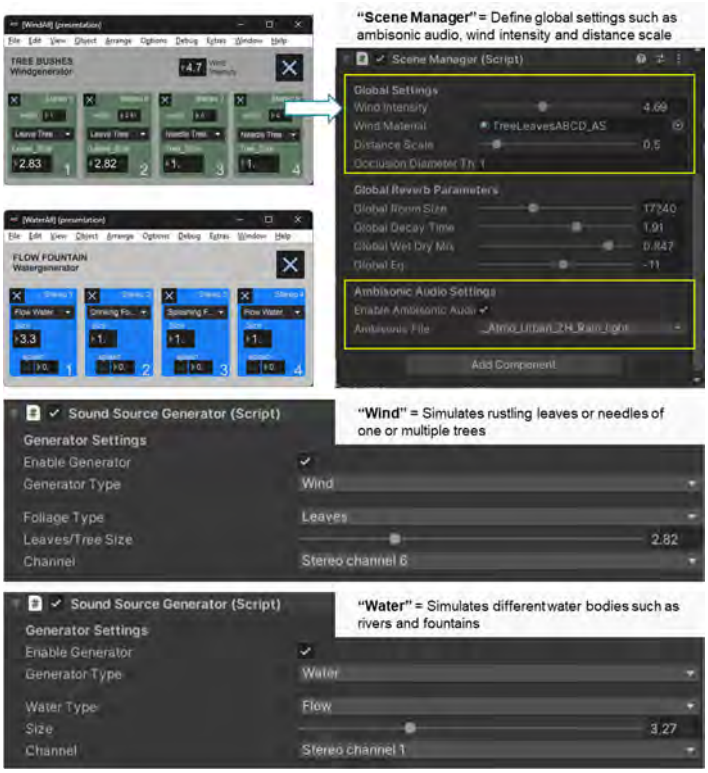

Fig. 3: Sound Source Generator component for wind and water generators that play sound samples according to parameter settings

The “Scene Manager” (Fig. 3), included in the “Settings” prefab (Fig. 2), handles global settings such as the wind intensity, which affects the wind generator and the generated sound respectively. The material for tree leaves is also affected by the wind intensity in terms of the motion speed. For providing a general environmental ambience, ambisonic audio can be enabled and a sound file chosen from the audio library’s “Ambisonics” folder. Further, thresholds of object areas to generate occlusion (if an object is between the listener and the source, the sound is occluded), as well as global reverb parameters (room size, decay time, wet/dry mix, EQ (a high shelf ranging from 0 – 20 dB) of the local reverb, radii/dimensions of the

reverb zone and the fading radius to another local reverb) can be set. The reverb zones were included to allow for "generic" reflection modelling using artificial reverberation (which is not derived from the actual scene geometry). With the "Reverb Zone" component, two local zones can be defined, and moving from one to the other zone will fade the parameter accordingly, whereas outside of these zones the general reverb applies.

Agile development continued during the implementation in courses, where students wanted, for instance, to switch between various scenarios and perspectives without free navigation as this was time-consuming and required training. Therefore, the "ScenarioChanger" prefab was developed in Unity. First, game objects are grouped into parent-objects "Scenarios" (e. g., Scenario1, Scenario2) with corresponding audio files assigned via the "Sound Source Audio" component (Fig. 2). These scenarios are then assigned in the "ChangingScenario" component. The "Player" object can be positioned as needed by providing the respective coordinates. In game mode, switching between scenarios or player positions is done via predefined keyboard keys.

2.3 Implementation and Evaluation

In spring semester 2025, the app was implemented in two Master's courses focusing on landscape acoustics and 3D landscape visualization respectively and feedback from student and lecturer perspective was collected. The app was used extensively in the courses. In "GIS-based 3D Landscape Visualization (GIS-VIS)", a prepared Unity scene demonstrated sound distribution, attenuation, and perceptual effects. Students then applied the app to improve realism in their individual 3D scenario simulations in the first study site (see chapter 2.2). In "Landscape Acoustics (LA)", students examined sound layering, masking effects, and room acoustics by placing real-world recordings into the 3D model of the second study site (see chapter 2.2), analyzing frequency ranges, and categorizing sounds into color-coded eco-acoustic groups. Further, they had to add new sounds and used the app to connect their spatial sound design with this 3D model to gain a better perception of scale.

A learning journal (GIS-VIS: N=31; not conducted in LA) was employed for the students to reflect on their performance and self-satisfaction and to receive systematic information on the students' learning progress. In addition, lecturer observations during the GIS-VIS course as well as an interview with the LA-lecturer after the course were conducted. Further, feedback was gained from students on the app's usability and its quality to support competence building in soundscape design and evaluation after the course using a group discussion and an online questionnaire with a 5-point Likert scale ranging from "strongly disagree", "somewhat disagree", "neither agree nor disagree", "somewhat agree", to "strongly agree", and the option "don't know" (GIS-VIS: N = 5; LA: N = 18).

The questionnaire included selected items from the Motivated Strategies for Learning Questionnaire (PINTRICH & DE GROOT 1990; Q1; 4; 5; 7; 11; 15; 17; 21; 44) to analyse students' learning strategies. Following items were added: "What we are learning on landscape acoustics and soundscape design is inspiring.", "Being able to apply this topic is important to me.", and "I have already started to implement some of the learned skills in my current studies and projects." Further, questions from a "Computer System Usability Questionnaire" (TULLIS & ALBERT 2008, 140ff; Q1-3; 5-7; 10, 11, 13-15; 18-19) addressed overall satisfaction, system usefulness, information quality, and interface quality. Questions on specific functions were added, such as "It was easy to understand and use the respective functions of the Unity-App

window and the Panoramix Mixer.", "The Unity-App helped me to better understand the spatial and perceptual interaction of different sound sources.", "The Unity-App helped me to develop my project ideas and make them audible.", "I found it helpful to relate to a visual 3D model for spatializing my semester project.", and "I would have preferred to work with sound only.". Comment fields were provided to allow the students to offer additional information on their choices, suggestions, or ideas for improvement of the app.

3 Strengths and Weaknesses of the Prototype

The reflection of the developer team on the observations and experiences from lecturer perspective as well as the students' feedback led to an overview of the prototype's strengths and weaknesses. In the following, major insights are presented.

From lecturer's perspective, using the app for certain theoretical inputs such as the soundscape's layered structure of sounds and to show interactions with the built environment, e. g., whether a source is masking other sounds or not, worked well. In contrast, demonstrating spatial acoustic effects such as occlusion or zones with different reverberation characteristics did not provide results perceived as realistic or caused malfunctioning of the app. Moreover, the extensive use of the audiovisual app limited the time needed to train students' spatial hearing skills. This training was more effective when students worked with sounds only, and listened to auralizations that were processed in a digital audio workstation and replayed through the lab's room audio system with loudspeakers.

Nevertheless, the majority of students found the overall topic important and liked what they were learning on landscape acoustics and soundscape design. They found the app somewhat (48 %) to strongly (30 %) helpful to better understand the spatial and perceptual interaction, to develop own project ideas (somewhat: 52 %; strongly: 30 %), and to relate to a visual 3D model for spatializing their sound project (LA students: somewhat: 50 %; strongly: 33 %). Students stated that the app was helpful to import sound files and perceive how they interact with the environment for quick tests. However, they rated their ability of soundscape analysis, design and evaluation still moderate (57%) to low (30%). Few students of the LA course indicated that they would have somewhat (11 %) to strongly (6 %) preferred to work with sounds only. Whereas the majority was able to complete the given tasks using the app, one third each found it not efficient, were undecided, or found it only somewhat efficient. Concerning the app's usability, they were rather unsatisfied as it is not easy to learn and use.

4 Discussion and Conclusion

Overall, the prototyping process can serve as an example how collaboration of experts with very different backgrounds and skills can be facilitated to successfully develop an app for soundscape simulation conceptualized as a teaching medium. Crucially, our approach ensured that real-world requirements and concepts are not lost, but rather translated into intuitive features through continuous stakeholder involvement in the prototyping process.

The involvement of a spatial audio expert trained to identify first the required functions and parameters of an app, helped to translate user requirements into programmable algorithms. Moreover, it led to a modular implementation concept, which allows enrichment of the app with further functions. The documentation of the prototyping workshop contains crucial

thoughts and decisions. This information is also valuable for the app's iterative enhancement. Revisiting the argumentations might help to decide what should be further done (or not) and for what reason. For example, it would be desirable to better integrate spatial acoustic effects into the app. Regarding occlusion, e. g., a hard occlusion (0 or 1) of buildings and a soft occlusion (float) of trees could be implemented. Further, reflection of the sound depending on ground materials (sealed, unsealed, vegetated) or facades (concrete, glass, vegetated) would be desirable. But if only a very simplified implementation is possible that corresponds little to reality, it must be critically examined if this is meaningful. Similar to visual landscape representations a suitable level of detail for the intended tasks needs to be defined.

What makes this app different from existing real-time soundscape design tools for non-acoustic experts, is the combination of two virtual 3D models, the visual and the acoustic. Particularly for contextualizing sounds and for getting aware of distances, the students appreciated the integration of the audio into the visual model. However, Tarlao and colleagues (2023) argue for the benefits of audio-only immersive environments as it sets the focus on the sound experience. Since we discovered shortcomings in the listening for designing, the app should offer functionalities to easily switch off the visual and concentrate on the audio only.

The use of the app did raise awareness of the importance of sound in landscape perception and motivated and enabled students to engage with the topic of soundscape in urban design. Regarding the students' feedback that the app is difficult to use, it needs to be considered that also other software packages for 3D visualization such as AutoCAD (AUTODESK n. d.), SketchUp (TRIMBLE n. d.) or ArcGIS Urban (ESRI n. d.) require some effort to master the functions. However, the app's documentation and tutorials respectively should be improved to support its use. To provide the information in a suitable form, the requirements of the targeted user groups should be considered. Some students asked for an overview of the tool's functions coming along with a video tutorial demonstrating the workflows in the software. Finally, using the app for perceptive evaluation of soundscapes requires further didactic guidance. Further investigations should compare the students' analyses of soundscapes at the actual sites with the ones working with the virtual representations.

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Perception of Pixels: Landscape Aestheticization in Participatory Social Media

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Abstract: Social media shapes landscape perception through image-first, algorithmically ranked feeds. This paper analyzes, via a comparative study of AlUla (Saudi Arabia) and Socotra (Yemen), how participatory Instagram practices contribute to landscape aesthetization. Using 800 'Top' posts and a multimodal framework combining visual semiotics, metadata analysis, and AI-assisted coding, we identify aesthetic homogenization and visibility concentration. Findings show algorithms and replication often privilege spectacle over ecological complexity, co-producing "Instagram landscapes" that reframe places as images rather than lived systems.

Keywords: Digital landscape, landscape homogenization, user-generated content, Instagram

1 Introduction

Landscape perception, grounded once in direct, embodied experience, includes the interaction of sensory dimensions such as visual, auditory, and olfactory experiences, which do not simply add up but result from multi-layered information processing and shape emotional responses, creating a holistic experience (CHEN et al. 2024). The fragmented views are overcome by a comprehensive understanding of the environment, including the complex interplay between sensory inputs and cognitive processes (SCATENA 2018). The growing reliance on digital platforms is turning personal encounters with place into interactions with curated visual narratives (SAN CORNELIO et al. 2024); perception occurs through digital images rather than through physical presence in the landscape (XING et al. 2024). Platforms actively reshape the emotional, cognitive, and behavioral dimensions of place attachment, as users co-produce place narratives and emotional engagement through digital interactions, including user-generated imagery, hashtags, and storytelling (SHI et al. 2025). While these platforms democratize landscape representation – allowing local communities, visitors, and activists to share their viewpoints – they also amplify selective aesthetics, simplify complex ecologies, produce new hierarchies of visibility, create homogenized impressions, and shape social norms of beauty and lifestyle (PUTRA & AFRILIAN 2025). The continuous flow of user-generated content creates new patterns of what is "beautiful," "authentic," or "worth preserving" (LI & YANG 2022). Social media (SM) images shape a standardized view of landscapes, supported by algorithms that are optimized for mass appeal and engagement, amplifying popular visuals at the expense of more diverse or unconventional ones (FURIA & ROMELE 2024). Algorithmic curation leads to the homogenization of content, and algorithms act as powerful agents in redefining aesthetic and cultural hierarchies. Therefore, platforms such as Instagram foster participatory aestheticization – a process of transforming landscapes into appealing objects that focuses only on their attractiveness (LAMBERTI 2025, LANGEMEYER et al. 2018). Repeated exposure to similar imagery eventually lessens emotional salience and contributes to anesthetization – perceptual "numbing" over time of sensory and emotional responses to

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scenery, leading to desensitization and, ultimately, apathy and emotionlessness to other layers of the landscape (MASTRIA et al. 2017). Additionally, the experience of landscape on a screen leads to spatial perception being cut into individual visual fragments (XING ET AL. 2024, LEE 2010), the effect similar to a windshield that limits and frames the driver's view (COLONNESE & ROSA 2021). It is contributing to a distorted and fragmented observation field.

This paper explores the role of participatory user-generated SM content in influencing and shaping collective perceptions of landscapes. The analysis builds on fieldwork and conceptual insights from the previous research (DREKSLER & BACHA 2025) and extends the inquiry toward a broader digital participatory framework. Two contrasting landscape narratives previously investigated in terms of tourism models and community participation – AlUla (Saudi Arabia) and Socotra (Yemen) – were analyzed with a mixed qualitative–quantitative exploration of participatory visual practices and collective landscape perception.

2 Materials and Methods

This exploratory study adopts a comparative case approach, using medium-sized datasets to identify aesthetic patterns, narrative tendencies, and perceptual framing, supported by multimodal content analysis. We gathered data from Instagram, the most popular photo and video-sharing social networking service[1]. We focused on the platform's most popular ('Top') results as an algorithmic visibility surface**,** aiming for 400 posts from each location. The sample size balances analytical depth with empirical robustness and is considered appropriate for systematic coding while still allowing close interpretive engagement (ROSE 2022, HIGHFIELD & LEAVER 2016). To ensure analytical consistency and comparability in the systematic coding, we used a uniform data type (static images) to isolate visual landscape attributes (color, composition, vegetation, spatial structure, materiality). We excluded video and content with audio, because dynamic visualizations engage different cognitive processes and analytical frameworks (PARRY 2020), and the effects of soundtracks, voiceovers, or cinematic techniques are external to the landscape itself. We initially scraped 400 posts per site from hashtag/geolocation queries (#alula, #socotra) and analyzed the publish dates returned by the 'Top' ranking. Data was collected using a multi-stage, sequential scraping process via the Apify platform (https://apify.com/) to ensure that distinct layers of metadata (Visual, Post-Level, and Account-Level) were fully captured. The data identification and acquisition were divided into 5 phases (Figure 1). Since some static images resulted with music metadata (which was identified in phase 3 – API Scraper), we excluded them and replaced for images without sound during sequential scraping process loop. From the final set of 400 images per site, we excluded reposts and commercial duplicates, which might disproportionately reflect platform algorithms and marketing strategies rather than independent user perception or landscape representation. Non-landscape images (portraits, products, events) were excluded because they do not directly represent the spatial or environmental constructs under investigation. We analyzed the final dataset manually, identifying major trends in the images' content in a four-category matrix instead of a single exclusion list, because many 'Top' posts mixed scenic imagery with promotion. We used manual screening logic: each image was classified

[1] With around three billion active users as of February 2025 according to https://www.statista.com/statistics/272014/global-social-networks-ranked-by-number-of-users/

on two dimensions – landscape visibility (visible/not visible) and promotional intent (yes/no). This produced four mutually exclusive categories: landscape, promotional with landscape, promotional without landscape, not landscape & not promotional. It captured an important distinction that the AI missed: an image can be visually landscape-rich and still function primarily as promotion. OpenAI ChatGPT (GPT-5.2, extended thinking mode enabled) was used mainly for aesthetic coding support (color, hue/saturation, framing proxies, motif suggestions)**,** for generating structured draft labels/captions and to support batch documentation across the image dataset. AI outputs were treated as heuristic suggestions and validated against the researchers' manual coding and were reviewed and corrected manually. All posts were public, and data collection complied with the platform's terms of service.

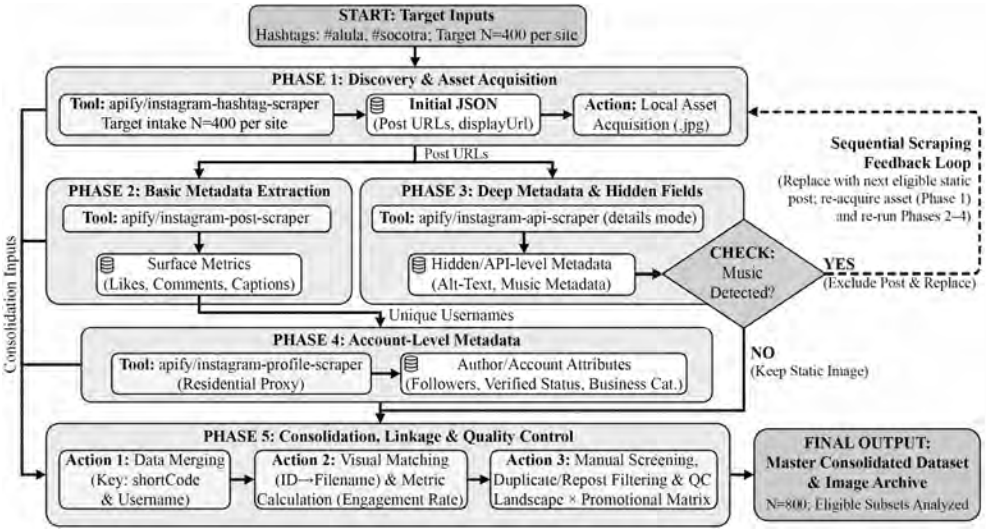

Fig. 1: Multi-stage sequential scraping process for data acquisition

The material was examined through three interconnected analytical lenses: **The aesthetic lens** explored image composition, motifs, formal conventions (color palette, horizon position, presence of people/nature interface) – *What do people show, and how do they frame it?* **The affective lens** assessed caption tone, emoji use, and engagement intensity, supported by basic sentiment analysis and co-hashtag frequency mapping – *What feelings accompany the images, and how does attention circulate?* **The socio-political lens** examined authorship, governance, and narrative intent through coding of account type and discourse positioning (institutional, commercial, grassroots, independent) – *Who is telling the story, and to what end?*

3 Results

400 static images were gathered for each site and analyzed for the landscape presence. After applying exclusion criteria (Table 1), we limited the number of images to 227 for AlUla and 263 for Socotra.

Table 1: Eligible and excluded images

	AlUla	**Socotra**
Posts format	platform-native and scroll-optimized: 60.0% carousels (Sidecar); 68.0% portrait framing	screen-native: 65.2% carousels (Sidecar); 60.0% portrait, 21.2% square, 18.8% landscape
Eligible images	56.75% (227/400) – carousels outperform single images	66% (263/400)
Excluded images	43.25% (173/400) – Promotional graphic/poster/text card: 113 (84/113 landscapes supported promotional ad), Others (portrait/people-centered, non-landscape object/interior, motorsport/vehicle-centered): 60	34% (137/400) – Promotional graphic/poster/text card: 96 (68/96 landscapes supported promotional ad), Others (portrait/people-centered, non-landscape): 41

The aesthetic lens. In AlUla, homogenization is measurable, and ecology is systematically de-emphasized. Among the 227 eligible landscape-dominant images, the feed collapses into extremely narrow scenic themes (Figure 2). Formal conventions of the eligible images include negative space (46.5%), warm colors, median dominant hue of 28° (warm sand/rock), and median saturation of 0.38. The 'Top' AlUla landscape (Figure 3) is optimized for the optically legible (horizon, emptiness, monumentality) while ecological texture is minimized and de-rewarded. Green color appears in only 2.5% of eligible landscapes, and its visibility is rare and penalized by attention. The oasis/vegetation refuge archetype is tiny (2.5%). The most popular object (32 images) is Elephant Rock (Figure 3b, 3c)

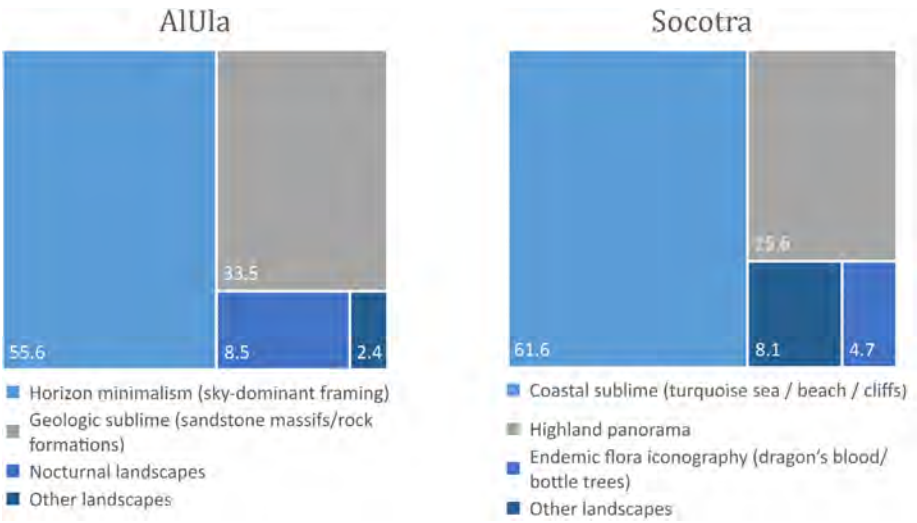

Fig. 2: Landscape archetypes for AlUla and Socotra in sample dataset

Socotra's 'Top' visibility produces a standardized paradise template (Figure 3d): sea/sky purity and panoramic altitude. Biodiversity is represented mostly by iconic dragon blood and bottle trees (94 images, Figure 3f). Composition conventions include negative space present in 70.3% of images; vertical portraits appear in 40.7% of images. Sky dominates strongly

with a ratio of 0.78 (versus 0.41 in AlUla); the median dominant hue is 206° cyan/blue dominance (sea/sky), and saturation is 0.27 (lower than AlUla). Green appears in 22.1% (endemic flora archetype, coastal landscapes), but is not rewarded as a dominant aesthetic, except in lagoon and wadi oasis, which have very high median likes.

Fig. 3: Representative 'Top' feed Instagram images[2] illustrating dominant landscape archetypes in AlUla: (a) Horizon minimalism (sky-dominant framing), (b) Geologic sublime (sandstone massifs/rock formations – in most cases famous Elephant Rock), (c) Nocturnal wonder (night-sky/illumination) and Socotra, (d) Coastal sublime (turquoise sea/beach/cliffs), (e) Highland panorama (mountain/plateau views), (f) Endemic flora iconography (dragon's blood/bottle trees)

Affective lens. Eligible AlUla landscapes are effectively repetitive with major themes of serenity/contemplation (55.6%) and awe/sublimity (33.5%). The emoji presence was detected in 44.4% of posts, and the images' captions were heavily tag-driven (median of 5 hashtags). The dominant affective register is "calm awe" – a mood that travels well on feeds, reinforces the "escape/sublime" trope, and aligns with scenic consumption more than situated understanding. In Socotra, the narrative is built around discovery and awe, but interaction remains

[2] Sources: (a) Valerio Salvi (@iovalo), Instagram post: https://www.instagram.com/p/DTHkHV-jJRg/;
(b) Cédric LD (@cedlediabat), Instagram post: https://www.instagram.com/p/DTTSYQbgkMC/;
(c) Miku Obara (@miku_0349), Instagram post: https://www.instagram.com/p/DTKoGbKE_Hf/;
(d) Untamed Borders (@untamedborders), Instagram post: https://www.instagram.com/p/DSj-loiiLYy/;
(e) Alena Chuprova (@alena_thegreat_), Instagram post: https://www.instagram.com/p/DTFYS2gjSqP/;
(f) @at_once_many_worlds (display name not provided in dataset), Instagram post: https://www.instagram.com/p/DSiKWuZDdzY/.

primarily metric-driven (likes) rather than dialogic. Awe/wonder was identified in 62.2%, while awe/adventure was identified in 26.2%. Emojis are present in 51.7%, and the median comment is 1, while 47.7% of eligible posts have zero comments.

Socio-political lens. In AlUla, institutional/commercial visibility behaves like broadcasting; smaller accounts generate proportionally "warmer" micro-publics. This is a clean empirical bridge to "new hierarchies of visibility" and "participatory aestheticization". The top 10% of posts capture 85.2% of all likes. Verified accounts contribute to 11% of posts, against 35% for business accounts. The followers' interaction is weak to moderate, and the the association between follower count and engagement rate is negative. Socotra shows a more explicit influencer-visibility structure: the top 10% of posts capture 93.5% of likes, while the top 10% of accounts capture 89.4% of likes. 9.2% of accounts are verified, and 32.5% represent business accounts. Institutional campaigns and high-follower influencers accelerate the homogenization in both cases, producing a globally recognizable "Instagram landscape aesthetic" that other users follow and replicate. Algorithmic curation reinforces specific affective tropes – serenity, awe, discovery – while marginalizing less visually striking or socially complex scenes. While many posts express emotional intimacy with place, the affective tone tends toward self-display. Emotional engagement thus fuels attachment without necessarily fostering deeper engagement.

4 Discussion

In AlUla, the 'Top' aesthetic is overwhelmingly horizon-minimalist and geologic-sublime, systematically filtering out vegetation and complex textures. Socotra is famous scientifically for its endemic flora, but the digital realm displays a different priority: coastal sublime (turquoise water/beach) dominates. The unique biological identity of Socotra is being selectively overwritten and visually homogenized. Our results show that Instagram visual norms extend beyond aesthetics of landscapes, shaping identity and cultural trends that can influence how landscapes are depicted and consumed through for instance unifying color palette preferences. Idealized representations investigated by PUTRA & AFRILIAN (2025) in context of human visual aesthetics extend to landscape creating a generic "global beach" and eroding diversity. By perceiving landscape through framed vistas (COLONNESE & ROSA 2021, LEE 2010), Instagram users are losing the context. The unconscious acceptance of the perfect image promoted by SM algorithms (FURIA & ROMELE 2024) leads to visual fatigue and indifference. We observed it as reduced engagement intensity in repetitive landscape scenes.

The patterns of participation in AlUla reinforce the shift from embodied experience to visual consumption, which is aligned with our previous research (DREKSLER & BACHA 2025). The lack of dialogue and interaction indicates that AlUla is treated as a museum exhibit or a product to be admired from a distance, not a "lived place", but a destination image optimized for branding. LI & YANG (2022) highlighted that SM offer more inclusive participation in capturing broader public views. But the landscapes we analysed are framed, homogenized and limited, overpowering local diversity. The users collaboratively create and reinforce attractive visual forms of landscapes following predominant (and often curated with filters) color palettes and visual motifs, supported by the algorithms which promote the same type of visuals, as discussed by SHI et al (2025). Digital participation promises democratization, but in visibility terms, the algorithmic reality is an extreme oligarchy, shaping a new realm of what is considered beautiful and worth displaying.

LAMBERTI (2025) claims that Instagram is not only a place for aesthetic consumption but also for exploration and discovery. Many people would not be aware of the existence of destinations such as AlUla and Socotra if they were not featured in SM. But repetitive exposure to the same content and the excessive visual stimulation leads to anesthetization – an aesthetic fatigue that diminishes people's interest in experiencing real space, as stated by XING et al. (2024) and MASTRIA et al. (2017).

5 Conclusion and Outlook

When the physical dimension of landscape experience is removed, perception becomes disembodied and image-driven, relying on visual surrogates – framed, edited, and algorithmically ordered representations. The meaning of a site is constructed through collective tagging, captioning, and algorithmic ranking. The loss of physical interaction narrows and anesthetizes perception to the optically legible: light, color, symmetry, and spectacle. Ecological and material diversity – weather, smell, uneven terrain – disappears, resulting in visually homogenized landscapes optimized for screen consumption. With a wide variety of landscapes in both locations, only three main landscape archetypes were consistently amplified in 'Top' feed visibility. Emotional responses are mediated through metrics (likes, shares, reactions) rather than through the lived atmosphere. Affective engagement was shaped by social feedback loops and visual trends, creating collective moods detached from direct environmental cues. The landscape is experienced as a temporal feed – an ever-renewing flow of representations rather than an inhabitable environment. This shifts perception from continuity and care to consumption and novelty. The body's sensory and spatial orientation is replaced by digital navigation and scrolling gestures. The removal of physical engagement turns places into signs – objects of cultural exchange and social identity rather than physical systems. Still, the potential of SM in raising awareness and more flexible participation should be acknowledged. Our study had some limitations. First, it was limited to 400 'Top' feeds. A larger sample drawn from a specific hashtag could identify fluctuations during a certain timeframe of the visual preferences of both the users and the algorithms. Secondly, we investigated only one SM platform, that is mostly used by a younger population. The results cannot be extrapolated to other platforms since they use different algorithms and both users and promotional circuits vary. Our scraped data is a temporal snapshot that could produce different results in another timeframe due to the character of the landscape or due to platform algorithmic changes. Finally, we limited our study to static images only. Video ethnography research could shed a different light on landscape perception in social media.

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Operationalizing Kairos: Digital-Twin Supported Participatory Action Research for Community-Driven Design

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Abstract: Landscape architecture's digital transformation is increasingly tied to collaborative, data-rich processes that blend community insights with computational modeling. We propose the integration of Kairos Moments, pivotal opportunities for timely reflection and action, into a digital twin-supported participatory design framework. In a one-year community design project in a mid-sized city in upstate New York, spatial data on heat, flood risk, walkability, and demographics were embedded in a web-based digital twin to facilitate stakeholder deliberation and iterative scenario development. The framework uses heuristic cues (based on Tversky & Kahneman's cognitive biases) to classify engagement episodes as representativeness, availability, or anchoring adjustments, which in turn flag Kairos Moments when collective decisions are most opportune. These moments serve as a bridge between real-world events and the digital twin environment, synchronizing community momentum with design interventions. Results indicate that the interactive digital twin improved transparency and allowed participants to visualize trade-offs, while the Kairos-based timing analytics enhanced stakeholder trust and foresight by aligning design actions with critical community readiness. We conclude with practical recommendations for embedding Kairos-informed, ethically grounded digital methods in participatory design practice and institutional policy.

Keywords: Digital twin, participatory action research, community support, Kairos moments

1 Introduction

Recent participatory and scenario-based approaches highlight a disciplinary shift from representational technologies toward collaborative digital infrastructures that mediate data, design, and deliberation (HOVERSTEN & SWAFFIELD 2019, IWANIEC et al. 2020). Yet despite advanced visualization and computation, digital participation often remains extractive when institutional timelines, funding cycles, or research goals eclipse community priorities. This paper responds to that challenge by introducing the concept of Kairos Moments, defined as critical windows of opportunity for reflection and action in participatory design. Such moments mark the opportune timing when interventions or decisions can have heightened impact, effectively serving as "wormholes" that tightly connect real-world community events with corresponding actions in the digital twin environment. These moments become an analytical and operational component within digital participatory workflows, ensuring that engagement happens at the most impactful times for the community. Without recognizing these Kairos opportunities, even well-intended projects risk missing key chances for building trust or achieving change, as misaligned timing can lead to lost momentum.

Drawing upon a Participatory Action Research (PAR) project addressing racial wealth disparities through urban design, we argue that Kairos can structure *when* and *how* interventions occur within digital workflows. The digital twin becomes both the site and the medium of co-creation: a shared, dynamic model where community knowledge, environmental data, and

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design alternatives converge to support collective decision-making. We define this synthesis as Kairos-informed participatory design, a process that integrates ethics of timing, trust, and stewardship into digital landscape practice. By explicitly considering *when* to engage (and not just *how* or *what* to design), the approach foregrounds an often-overlooked dimension of equitable participation, the timing of decisions, as a key determinant of ethical and sustainable outcomes.

2 Background and Conceptual Framework

2.1 Participatory Action Research (PAR) and Design Justice

PAR has long bridged research and social transformation by positioning community members as co-creators of knowledge (KINDON et al. 2007, WALKER & LOOTS 2018). Within the built-environment disciplines, PAR's iterative inquiry-action cycle (visioning, planning, implementing, evaluating) supports design processes grounded in reciprocity and long-term stewardship. The theoretical foundations of PAR originate from Paulo Freire's critical pedagogy, which posits that those affected by oppression must be co-creators of knowledge in order to achieve liberation (FREIRE 1972). In practice, PAR shifts the focus from knowledge *extraction* to collaborative knowledge production, directly involving community partners in defining problems and solutions. Complementing PAR, Design Justice (COSTANZA-CHOCK 2020) challenges "who designs, for whom, and with what power." Embedding Design Justice principles in digital workflows helps redistribute authorship from the expert to the community and transforms digital tools from passive visualization devices into active instruments of social negotiation. Together, PAR and Design Justice provide an ethical scaffolding for our digital twin methodology, ensuring that technology-enabled design is guided by principles of equity, inclusion, and mutual learning.

2.2 Kairos Moments as Temporal Ethics

In classical rhetoric, Kairos denotes the right or opportune moment for action (RÄMÖ 2004). Applied to community design, it reframes participation as a temporal as well as procedural challenge. Ferguson et al. (2017) and Manzini (2015) note that trust and care require synchronization between institutional readiness and community momentum. We therefore define Kairos Moments as decision nodes within participatory workflows where timing and responsiveness determine ethical quality. In other words, a participatory process is not only judged by what decisions are made, but when they are made in relation to community readiness. By operationalizing Kairos through a digital twin, we convert an abstract ethical notion of timing into measurable, interactive events: for example, when data thresholds are crossed, when feedback loops close, or when stakeholder consensus suddenly emerges. Each such event provides a digital trace of how and when collaboration occurs, allowing the project team to monitor whether engagement is keeping pace with community needs. Critically, failing to act during a Kairos Moment, due to delayed action or misaligned priorities, risks a missed opportunity that can erode trust or stall progress. Identifying these moments in real time thus becomes a strategy for prompt reflection and action, aligning design decisions with the lived temporal rhythms of the community.

2.3 Digital Twins and Participatory Design

The scenario-based digital twin, a dynamic, data-linked virtual model continuously updated with real-world feedback, extends traditional GIS and visualization tools into decision-support systems for socio-ecological design (MAHMOUD et al. 2009, WILLIAMS et al. 2023). In this project, the twin functions as both analytic and pedagogical infrastructure, enabling community members to visualize how physical design interventions could influence well-being indicators such as shade coverage, ambient temperature, flood risk, and accessibility. Integrating the twin with a PAR approach transforms it into a living participatory model where each iteration reflects both data and dialogue. Rather than using the digital model merely to display outcomes, participants directly interact with it, adjusting parameters, testing scenarios, and seeing immediate feedback, thereby co-creating knowledge. This interactivity means the digital twin is not a static representation but a facilitative space where stakeholder input and quantitative analysis inform each other. By logging interactions and discussions within the twin, the system can highlight when engagement peaks or when new information significantly shifts the discourse. These capabilities set the stage for embedding Kairos Moments: the twin helps reveal when critical shifts occur and provides a medium to capitalize on them, effectively synchronizing the "virtual" design process with real-world community dynamics.

3 Methodology

3.1 Study Context

The case study was a one-year participatory design project (2022-2023) in a mid-sized city in upstate New York, examining how environmental design interventions can promote economic and social equity in historically marginalized neighborhoods. Using PAR protocols, the research team collaborated with local community organizations and municipal agencies to co-define project objectives, design criteria, and evaluation metrics. This project specifically addressed aspects of the racial wealth gap through urban design strategies (such as improvements to public spaces and infrastructure in underserved areas). The effort faced several practical challenges that underscore the importance of timing and trust: for instance, initial delays in funding disbursement and municipal approvals created lags in the schedule, and community members expressed skepticism rooted in "research fatigue" from past planning initiatives. These conditions made it clear that building trust and aligning the project timeline with community readiness were paramount. In response, the team explicitly incorporated mechanisms (described below) to identify and act upon critical moments when stakeholder engagement was high and consensus was emerging. All community participation followed ethical guidelines and was facilitated through a series of public workshops and design charrettes conducted over the project year.

3.2 Digital-Twin Workflow

The workflow integrates four stages, each leveraging the digital twin platform to support participatory planning:

1. **Data Integration:** Multi-scalar spatial datasets (e. g. socio-ecological indices, surface temperature maps, tree-canopy density, walkability scores, floodplain extents, and demographic statistics) were compiled and ingested into a GIS-based digital twin environ-

ment. We utilized a suite of tools (ArcGIS Pro, ArcGIS Online, CityEngine, and BIM/ Revit for 3D modeling) to create a realistic, interactive model of the study area. Data layers were visualized through web-based interactive dashboards, enabling participants to toggle layers and explore current conditions as a foundation for participatory analysis.

2. **Participatory Modeling:** Stakeholders and researchers engaged with the twin during a series of workshops (5) with an average of 5 participants via a browser-based interface. In real time, participants could adjust planning parameters or design features, such as adjusting land-use allocations, adding green infrastructure, or altering public space accessibility, and then immediately visualize the projected impacts. For example, community members experimented with scenarios like increasing street-tree coverage on certain blocks to see modeled reductions in heat islands. This hands-on modeling encouraged collaborative exploration of alternatives and helped surface preferences by showing tangible outcomes of each idea. The digital twin thus acted as a common ground for discussion, where quantitative simulations informed qualitative deliberations.
3. **Kairos Identification:** We embedded a heuristic decision-support logic into the workflow to identify Kairos Moments. Drawing on Tversky & Kahneman's (1974) cognitive heuristics, we manually coded engagement episodes (from workshop transcripts and digital interaction logs) for three types of cues:
    - **Representativeness** – instances where proposals or comments reflected familiar community norms or prototypes (e. g. a resident suggesting a solution that mirrors a successful past initiative in the neighborhood).
    - **Availability** – the frequency and intensity of recurring priorities in discussion (e. g. a particular concern like "shade for playgrounds" being raised repeatedly by multiple participants, indicating it is top-of-mind and collectively salient).
    - **Adjustment from Anchor** – evidence of a significant change in stakeholder stance after new data or visualization appeared (e. g. a participant revising their position on a housing density issue once shown flood risk maps, demonstrating a shift from an initial anchored viewpoint).
4. Each workshop transcript was reviewed using a structured qualitative coding convention. For reproducibility, each Heuristic indicator such as Representativeness, Availability of Instances, and Adjustment from the Anchor, was analyzed through explicit coding definitions, keyword families, and observable behavioral marks. The research team conducted an initial rubric to evaluate, calibrate, and revise inputs to the digital twin being it was the decision tool for the project. We selected a manual and thematic qualitative coding approach due to the moderate dataset size and the contextual nuance required in the deliberative dialogue. This approach was supplemented with structured quantitative measures. A 'crosswalk' was generated where we analyzed topic frequency counts with applicable digital twin data inputs to corroborate 'Availability of Instances' cues and digital twin variables or parametrization criteria associated with 'Adjustment from the Achor' effects.

    A Kairos Moment was recorded only when multiple independent indicators converged during that period of time or meeting series. In short, thematic repetition was an indicator of a Kairos Moment in terms of intensity. By combining explicit coding definitions, parameterization through the crosswalk, and identification of Representativeness, Availability of Instances, and Adjustment from the Achor, the workflow provides a replicable framework for future researchers to operationalize in similar studies.

Activation and Response: Once a Kairos Moment was identified (either during the session or in post-analysis), the facilitators would intentionally *activate* it by guiding the group to reflect or decide on that issue while momentum was high. In practice, this meant adjusting the engagement strategy or design process in real time or in subsequent meetings. For example, if the heuristics indicated a surge of support for a certain idea (as with the shade intervention), the team would allocate extra time in the agenda to develop that idea further or fast-track a detailed design exercise around it. In some cases, activation involved aligning external actions with the moment: after a consensus on a market pavilion design emerged, the team coordinated with a municipal grant opportunity that was open at that time, to seize the funding *window* for implementation. The goal of this stage was to ensure that identified Kairos Moments were not merely observed, but translated into concrete adjustments, be it a design decision, a policy proposal, or scheduling the next engagement at an optimal time. In essence, the digital twin's Kairos monitoring became a prompt for timely action, helping the project remain responsive to the community's rhythms.

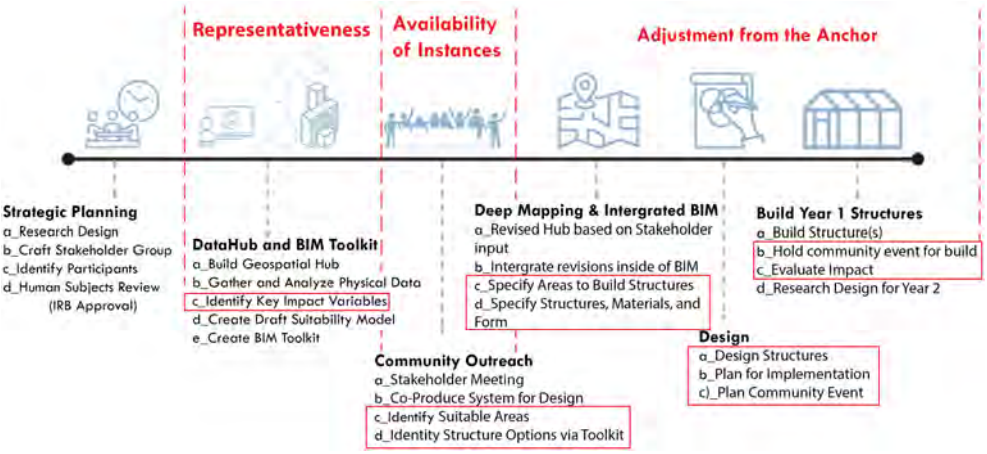

Fig. 1: This diagram illustrates our workflow within the case study, including data integration, participatory modeling, and the identification of key Kairos Moments via heuristic cues

3.3 Engagement Methods

A mixed-methods participatory approach was used to carry out the project, combining multiple forms of engagement and data collection:

- **Community-Led Workshops** (n = 5): These facilitated sessions (each 2-3 hours long) brought together residents, local leaders, municipal staff, and researchers to co-create goals, assess digital twin scenarios, and review design proposals. An average of 5 participants participated in workshops. Activities included group discussions, mapping exercises using the digital twin interface, and priority-voting on design options.
- **Semi-Structured Interviews:** Outside of the workshops, we conducted one-on-one or small-group interviews with key stakeholders (residents of the focus neighborhoods, city planners, and local NGO representatives). These interviews provided deeper insight into personal experiences, historical context, and stakeholder values, which informed how we interpreted workshop outcomes and refined the digital twin's data.

- **Design Charrettes:** Toward the latter part of the project, we hosted intensive design charrette sessions to translate digital scenarios into tangible spatial interventions. For example, one charrette focused on developing a modular shade pavilion concept for a neighborhood marketplace, taking the idea (which emerged in workshops as a priority) and sketching out its form, materials, and placement on the digital twin model. These charrettes allowed participants to move from abstract scenario exploration to concrete design prototyping.

Digital Trace Analytics: Throughout the engagement, the digital platform logged user interactions (e. g. which layers were toggled, which scenario comparison views were opened) and we timestamped discussion themes from video recordings. These interaction logs and transcripts formed a digital trace of the participatory process, which we later analyzed to understand the timing and frequency of stakeholder inputs. This data was crucial for the Kairos identification described above, effectively linking *what* participants did and said with when they did so.

3.4 Evaluation Criteria

We evaluated the process and outcomes using three main dimensions, reflecting both the efficacy of the digital tools and the quality of the participation:

- **Digital Effectiveness:** Assessed the usability and comprehension of the digital twin interface. We collected feedback through post-workshop questionnaires and observations, looking at whether participants could easily navigate the tools, understand the visualizations, and gain insights from the simulations.
- **Collaborative Efficacy:** Examined the diversity and equality of participation. Using dialogue transcripts and facilitator notes, we coded interactions to see if a broad range of voices were contributing (versus one or two people dominating) and whether traditionally marginalized community members felt empowered to speak. This criterion was influenced by Design Justice principles. Success meant that community knowledge genuinely drove the dialogue. We also noted instances of co-learning or consensus-building as signs of effective collaboration.
- **Temporal Responsiveness:** Measured how the identification of Kairos Moments influenced the project's decisions and timing. We tracked the frequency of Kairos Moments (e. g. how many were identified per workshop, with a total of 23 across all sessions) and evaluated their impact on subsequent design decisions or actions. For instance, if a Kairos Moment was identified around the need for shade structures, did that directly lead to incorporating a shade pavilion in the final design proposal or adjusting the project timeline to pursue a funding opportunity? A high temporal responsiveness score would indicate that the process successfully synchronized engagement timing with decision-making; essentially, that the team "caught" the critical moments and acted on them.

By triangulating these criteria, we aimed to get a holistic sense of how well the digital twin-supported process worked, not just in producing a plan but in doing so ethically and effectively from the participants' perspective.

4 Results

4.1 Digital Twin as a Collaborative Medium

The interactive digital twin proved to be an effective collaborative medium, enhancing transparency and shared understanding in the design process. It translated complex environmental data into legible visual narratives that all participants could grasp, irrespective of technical background. Users reported greater trust in the data when they could manipulate parameters themselves and instantly see spatial outcomes reflected on the map or 3D model. This aligns with findings by Iwaniec et al. (2020) on the co-production of sustainable scenarios, where stakeholder engagement with scenario tools builds confidence in outcomes. The twin's dashboard interface allowed side-by-side comparisons (e. g. before vs. after or Scenario A vs. Scenario B), which helped clarify trade-offs between different design options. For example, participants explored scenarios to increase tree canopy in various locations and could visually compare how each scenario affected summertime air temperature, shaded public space, and implementation feasibility. These comparative visualizations led to more informed deliberations: the group could point to the screen and say, "If we add trees here, we gain shade but might reduce open play space, how do we balance that?" In essence, the technology shifted the dynamic from abstract debate to evidence-informed negotiation, where participants collectively interpreted model outputs. Several participants noted that seeing their ideas reflected immediately in the digital model made them feel heard and validated. This interactive process also fostered inter-stakeholder trust: community members and officials alike gained confidence that decisions were based on transparent data, and community members felt a sense of ownership over the emerging designs. One practical outcome of this approach was that it surfaced creative solutions with broad support, most notably, the concept of a modular shade pavilion for the neighborhood market, which emerged from the twin-enabled discussions and quickly became a centerpiece of the design proposal.

4.2 Detection and Activation of Kairos Moments

Across the five workshops, we recorded 23 distinct Kairos Moments, which are instances where the combination of stakeholder input and digital feedback triggered a notable shift in collective priorities or the direction of design discussions. Analyzing these moments revealed three recurring typologies of Kairos in this context:

Data-Driven Kairos: Moments sparked directly by the visualization of new data or model outputs. For example, when the twin displayed a heat-island intensity map of the city, participants immediately recognized the stark temperature differences in their neighborhood. This prompted an instant surge of advocacy for tree canopy interventions (planting street trees, adding shade structures), a pivot in the discussion that might not have occurred without seeing the data. In this case, the data visualization acted as a catalyst in which participants' availability heuristic kicked in as the freshly seen extreme heat problem dominated their attention, and a representative solution (more trees, a familiar community response to heat) was readily proposed. The digital twin log showed a spike in interactions (many users turning on the "temperature" layer and sketching tree locations) exactly at this juncture, confirming it as a Kairos Moment driven by data revelation.

Socio-Political Kairos: Moments emerging from social dynamics, value discussions, or power-related considerations within the group. For instance, during one workshop the conversation shifted to long-term maintenance of proposed interventions. A community elder raised a concern: "Who will own and care for these new public spaces?" This led to a deep discussion about ownership, stewardship, and equity, especially when the twin was used to highlight that certain vacant lots (potential project sites) were city-owned versus community-owned. That realization, which combined factual information (ownership status) with community values, created a window where participants reevaluated design priorities to ensure local stewardship was feasible. The representativeness cue was evident here as well: participants invoked local precedents (e. g. a nearby community garden run by residents) as models for how any new space should be managed. This socio-political Kairos Moment resulted in adding a requirement that any design proposal include a community stewardship plan, aligning the project more closely with local values.

Institutional Kairos: Moments tied to external institutional timing and constraints, where aligning the project's actions with these larger rhythms was crucial. For example, in one instance the team discovered that a municipal grant for green infrastructure was accepting applications shortly after the final workshop. Meanwhile, in that workshop, the community achieved consensus on a green streets proposal (bioswales and tree planting along a particular corridor). This coincidence of community readiness (having a concrete, supported plan) and an institutional opportunity (funding availability) was a classic Institutional Kairos Moment. We recognized it as such and shifted immediately into drafting a grant application with community input, so as not to miss the funding window. Conversely, we also documented a case of missed Institutional Kairos: a proposed affordable housing design from the project aligned with a city initiative, but bureaucratic delays in our collaboration caused the timeline to slip past the city's budget cycle, losing a year before the next opportunity. These experiences underscore that Institutional Kairos is often the most challenging to harness. It depends on factors beyond the immediate control of the community or facilitators, yet it can make or break a project's ultimate implementation. In our analysis, Institutional Kairos moments were fewer in number than the other types, but when they occurred they had outsized impact on whether project ideas advanced toward real-world action.

Notably, nearly all identified Kairos Moments coincided with peaks in user interaction within the digital twin, which validates our heuristic classification approach. In the moments described above, the digital trace data showed increased activity (layer toggling, scenario adjustments) precisely when participants were most animated in discussion. This correlation suggests that our method of detecting representativeness/availability/anchor-adjustment cues was capturing real inflection points in engagement. Figure 1 (Section 3.2) charted these moments along the project timeline; we observed, for example, a cluster of data-driven Kairos spikes in the early workshops (when baseline data was first introduced), and more socio-political and institutional spikes in later stages (as designs solidified and external partnerships came into play). The end result was a more synchronized process. Decisions about design changes or next steps were taken at times that felt natural and right to the participants, rather than according to a rigid pre-set schedule.

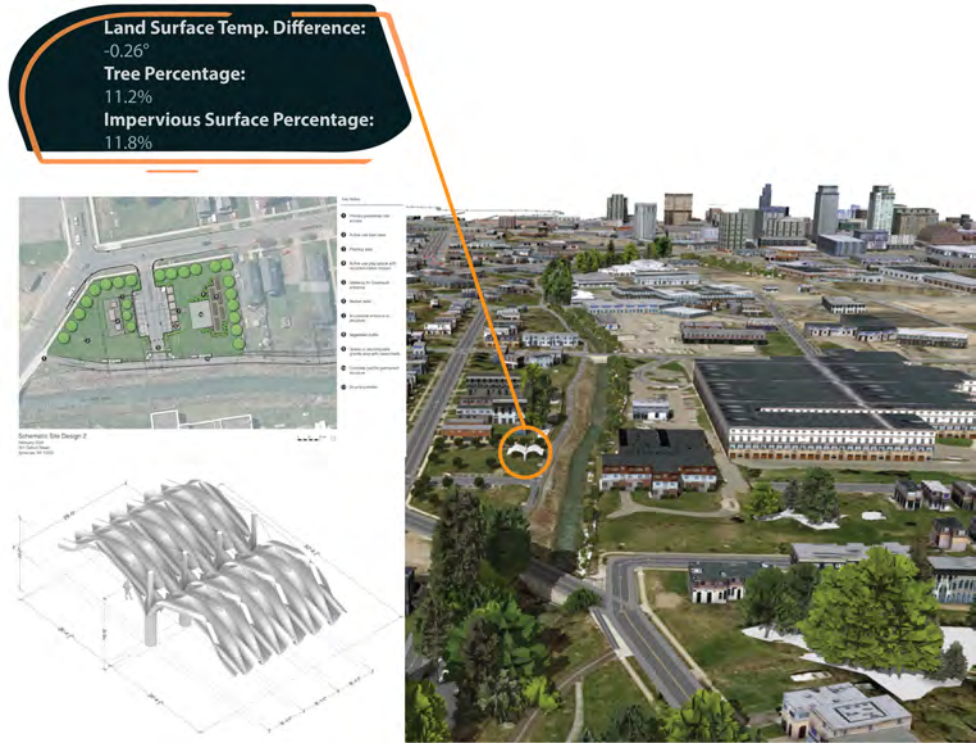

Fig. 2: Shade Structure Detail and Digital Twin

4.3 Ethical and Temporal Outcomes

Implementing the Kairos framework yielded several notable outcomes related to the ethics of timing and overall participant experience. First, it significantly improved the responsiveness of the project by synchronizing institutional action with community momentum. In instances where we successfully activated a Kairos Moment, stakeholders saw nearly immediate follow-through. For example, after the consensus on the shade pavilion idea (a socio-political Kairos moment), the research team helped channel resources to develop that concept further and initiated talks with the city about a quick implementation pilot. This kind of prompt response reinforced to participants that their input carried real weight. One community member commented in a post-workshop interview that "in past meetings, we'd give ideas and never know what happened. Here, we could see our idea taking shape on the screen and then see it move forward in the real world." Such feedback indicates a higher level of trust and satisfaction with the process. Indeed, participants overall articulated greater satisfaction with the transparency and reactivity of the engagement. They reported feeling that the process was not just a formality, but a living collaboration where their input had tangible effects on the final outcomes.

The flip side was also instructive: delays due to bureaucratic constraints were documented as "missed Kairos," underscoring the ethical cost of inaction or misaligned timing. For example, as mentioned, one promising design proposal lost some momentum when it couldn't be pur-

sued immediately because of external red tape. We openly discussed this with the community in a debrief, framing it as a missed Kairos Moment. While disappointing, that discussion itself was valuable. It validated the community's frustration and highlighted exactly where institutional processes need to change to better support grassroots initiatives. In terms of measured impact, our Temporal Responsiveness criterion captured these dynamics: we found that a majority of the design decisions that made it into the final plan were traceable to identified Kairos Moments (i. e. they occurred either during or shortly after those moments). This suggests that by paying attention to timing, the team was able to focus on and elevate the ideas that had the strongest authentic backing.

An ethical insight from this approach is the importance of pacing and patience. While the digital twin technology enabled rapid exploration of ideas, the Kairos perspective reminded us that there are optimal times to pause and reflect. In practice, some workshops ended a bit early on content because we sensed the group had hit a significant realization (i. e., a Kairos point) and it was better to let that marinate and reconvene later than to push on. Participants later noted that this pacing, doing the "right thing at the right time," made the engagement feel more respectful and less rushed than typical planning meetings. In summary, the integration of Kairos Moments into the participatory digital twin workflow enhanced both the effectiveness and the ethical grounding of the project. By the end, the community not only had a set of co-created design proposals (such as the shade pavilion and green infrastructure projects) but also a greater confidence that the process honored their timing and readiness. Several stakeholders expressed that they felt a stronger sense of stewardship over the outcomes, having seen how their collective moments of decision were recognized and acted upon in a timely manner.

5 Discussion

5.1 From Representation to Relationship

Traditional digital tools in landscape architecture often prioritize precision and photorealistic representation of proposals. In contrast, the Kairos-twin framework reorients these technologies toward what might be called relational ethics: the timing and context of engagement become as critical as the accuracy of data or visuals. By making moments of decision visible and salient, the system transforms what is usually an abstract or hidden aspect of collaboration (the ebb and flow of participant readiness) into a traceable, discussable, and ultimately actionable process. In our case, participants could literally see when a decision node had been reached. For instance, we observed that "everyone was silent when that map came up, which means we were all thinking hard about it." Such meta-cognitive awareness, facilitated by the digital trace, began to shift the group's perspective from simply generating content (ideas, maps, and designs) to also minding the health of the process (relationships, trust, and timing). This supports a broader conceptual shift: digital participation tools should not only represent biophysical conditions but also foster relationships between stakeholders, and between people and data through careful attention to when and how information is introduced. In essence, the Kairos approach pushes digital landscape practice beyond just delivering scenarios toward cultivating a mutual readiness to act. The visible logging of decisions and moments also made the process auditable in hindsight; community members and external observers could review the timeline of engagement and see why certain decisions were made when they were. This kind of accountability is rarely available in standard design charrettes. Thus, emphasiz-

eng timing (Kairos) alongside content turns the participatory design into a relationship-centered practice, where trust and ethical alignment are built into the very sequence of interactions, not treated as an afterthought.

5.2 Integrating Heuristics with Participatory Design

Adapting Tversky and Kahneman's (1974) cognitive heuristics for community engagement proved to be a novel but effective means of quantifying and mapping decision behavior in a qualitative design process. In our framework, representativeness, availability, and adjustment from anchor served not only as cognitive descriptors of individual behavior, but as participatory design analytics essentially, measures of inclusivity, salience, and adaptability in group decision-making. Embedding these metrics within the digital twin interface encouraged a form of reflexive practice among participants and facilitators alike. For example, when the group saw (through facilitated feedback) that many of their ideas were clustering around familiar solutions (high representativeness), it prompted a discussion about whether they were overlooking innovative options. In other words, it made bias visible in a non-confrontational way. Likewise, noticing that a particular concern (e. g., flood risk) kept coming up (high availability) helped justify dedicating more time and consideration to that issue in the design. This use of heuristics provided a common vocabulary for the team to analyze the collaboration itself.

Importantly, integrating heuristics did not mean reducing the richness of participation to numbers. Rather, it added a light layer of structure that supported the human interpretation of complex discussions. It also opens up possibilities for replication in other settings. The heuristic categories are general enough that other participatory design projects could adopt similar coding to monitor their processes. The successful example we provided (coding a repeated comment about shade as an availability cue) illustrates how straightforward yet powerful this can be. Of course, one must be cautious: heuristics are simplifications of cognition and can't capture everything. But in our experience, they captured enough of the pattern of interactions to be a useful guide. Moving forward, it would be interesting to experiment with partially automating this (e. g., using text mining to flag repeated phrases for availability), but we suspect a human-in-the-loop approach will remain crucial for nuanced interpretation. In summary, the marriage of cognitive science and participatory design in this framework helped bridge qualitative and quantitative realms, encouraging participants to reflect on how they decide, not just what they decide. This reflexivity, in turn, can lead to more deliberate and democratic decision-making processes.

5.3 Implications for Landscape Education and Research

For academic programs and researchers pursuing advanced digital pedagogy, the workflow presented here offers a template for teaching what we might call ethical computation in design. In typical landscape architecture or landscape planning studios, students learn to use digital tools for analysis and visualization; we suggest extending this to also train students in reading the room and responding to the social timing of decisions. A studio using a Kairos-informed digital twin might, for example, have students play roles as facilitators who must decide when to switch tasks based on participant feedback analytics. This could cultivate a new skill set around dynamic facilitation and process ethics, alongside technical GIS/BIM skills. Additionally, this framework contributes to research on participatory modeling by providing a method to evaluate when engagement is effective. Future research could build

on our evaluation criteria, especially Temporal Responsiveness, to compare projects that use Kairos principles vs. those that don't. Such comparative studies could offer evidence on whether explicitly timing-aware processes yield better long-term outcomes (e. g. more sustained community involvement, or design implementations that stick). Another educational implication lies in interdisciplinary collaboration: our project drew on concepts from psychology (heuristics), rhetoric (Kairos), and data science (digital twins). This underscores the value of breaking silos; landscape architecture curricula might incorporate basic training in these other fields to equip future practitioners for such integrative work. Finally, there is an opportunity for open-source development: given that many components of our digital twin and analysis approach can be coded, universities could develop shared platforms or toolkits that embed Kairos monitoring into commonly used participatory planning software, making this approach more accessible and standardized for widespread adoption.

5.4 Policy and Institutional Reform

Our findings echo a broader argument in the literature and practice: achieving sustainable and equitable digital engagement demands institutional change, not just better tools. In particular, the concept of Institutional Kairos emerged as a critical, and often problematic, factor in our project. The timing of funding calls, grant cycles, and bureaucratic procedures at universities or city agencies often did not align with the community's timeline for momentum and trust-building. As Springer & Skolarus (2019) observe, short-term project funding rarely accommodates the temporal realities of building trust. This misalignment led directly to some of the "missed Kairos" moments we noted. To address this, institutions need to consciously create conditions that allow participatory projects to seize opportune moments rather than be stymied by red tape. In practice, this could mean establishing more flexible funding mechanisms that can be quickly tapped when community consensus is reached, or adopting rolling timelines for project deliverables that can adjust to community pacing. Ferguson et al. (2017) similarly highlight that synchronization between institutional readiness and community momentum is vital. Our work puts a fine point on that by showing what is lost when the two fall out of sync.

We propose several policy-level reforms inspired by our case experience: (a) Universities and public agencies should adopt multi-year participatory frameworks with built-in flexibility, rather than one-year grant cycles that force artificial deadlines. Longer engagement horizons, with periodic checkpoints rather than a hard stop, would better accommodate the ebb and flow of community work and enable capturing Kairos Moments whenever they arise. (b) Funding bodies might consider small discretionary pools of money that community-academic partnerships can draw on swiftly when an opportunity (Institutional Kairos) appears. For example, a sudden chance to acquire a property or implement a pilot project that has community support. (c) Research institutions should allocate a portion of indirect costs or overhead returns to support community partners (e. g. honoraria, childcare for meetings, technical assistance) over extended periods, acknowledging that trust and relationships require continual investment. And (d) establishing Community Advisory Boards to oversee ethical issues in digital data use and to co-manage project timelines can institutionalize a more relational model of partnership (BOYER 1996, DRISCOLL 2008). Such boards could literally have a say in adjusting project schedules if community members feel things are moving too fast or too slow.

Implementing these kinds of changes would operationalize the shift from transactional, one-off projects to relational, long-term engagement models (BOYER 1996). They directly address the barriers we encountered under the umbrella of Institutional Kairos. Ultimately, institutions that embrace these reforms are more likely to see successful outcomes from participatory initiatives, because they empower projects to act in time with the communities they serve. An encouraging sign is that some grant programs and city governments are already reflecting on these needs. Our work adds empirical backing and a framework (Kairos-informed design) that could guide policy in practical terms. In summary, for digital participatory tools like ours to reach their full potential, they must be coupled with institutional practices that honor the ethic of timing as much as the outcomes of design.

6 Conclusion

This research has demonstrated how Kairos Moments can be operationalized within a digital landscape architecture framework, merging temporal ethics with participatory action and design innovation. Our case study shows that digital twins can do more than visualize environmental conditions. They can also visualize and record the co-production relationships in time, instilling greater community stewardship and trust in the design process. By capturing when collaboration occurs and how data influences decisions, the Kairos-twin workflow transforms participatory design from a reactive, check-the-box consultation exercise into a proactive co-creation process where community insight drives not only what gets decided but when it gets decided.

Key outcomes of our study include:

1. A replicable workflow linking PAR, Design Justice principles, and digital-twin technologies to support equitable community engagement.
2. A heuristic model for identifying and responding to Kairos Moments, providing designers and facilitators with a practical tool to gauge and enhance the timing of participatory interventions.
3. Empirical evidence that raising awareness of timing (through Kairos analytics) can enhance trust and decision quality, as stakeholders feel heard at the right moments and see timely action on their input.

For future research, there are rich opportunities to scale and generalize this approach. Future work will apply the Kairos-informed digital twin framework across diverse socio-ecological contexts. For example, in regional climate resilience planning, in co-designing green infrastructure for flood-prone communities, and in partnerships with Tribal Nations on land stewardship initiatives. Each context will no doubt reveal new types of Kairos Moments and additional heuristics that matter. By iteratively testing and refining the method, we aim to develop a more robust theory of participatory timing that could complement existing landscape planning models.

In closing, embedding Kairos within digital landscape practices ensures that technology truly serves community values. It helps practitioners remember that timeliness of design engagement is as crucial as the design content. As the field of landscape architecture continues to embrace big data, simulations, and digital twins, frameworks like this can keep those innovations grounded in human relationships and ethical principles. We envision a digitally enabled, ethically grounded, and temporally aware practice of landscape architecture, one where

community co-design is not only inclusive and data-informed, but also timed to meet the needs of the community.

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Interpersonal Interaction in Virtual Landscapes: The Effect of Color

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Abstract: This research examines how color affects interpersonal interaction in virtual landscapes. Proxemics has examined interpersonal distance in virtual landscapes and its regulation as a part of environmental stability, spatial cues, and perceptual clarity. Basic perceptual concepts, such as color and its effects on interpersonal interaction when physical cues are altered, need to be examined. Twenty-five participants participated in a controlled virtual-landscape experiment conducted in a natural landscape rendered under two visual conditions: colored and monochrome. Spatial data and questionnaires were used to measure distance, stability, comfort, and willingness to engage. While average interpersonal distance remained unchanged, movements in the monochrome visual landscapes were more variable and less controlled. Color-enhanced perceptual clarity enables steadier spatial behavior. These results highlight that color functions as a perceptual anchor in virtual landscapes, stabilizing interpersonal interaction without altering comfort levels. The research contributes to the understanding of proxemic behavior by describing how users adjust interpersonal distance during interaction in digital landscapes. It also provides methodology for designing perceptually balanced virtual landscapes.

Keywords: Virtual landscape, color, interpersonal interaction, effect

1 Introduction

No human experiences a truly colorless, monochrome space. Color blindness is a condition in which a person is deficient in a specific range of colors, but they are not truly blind to color and thus are not limited to seeing the world in monochrome (BIRCH 2001). For designs intended to shape the physical environment, previous studies of environmental perception in response to color versus black-and-white images and color versus black-and-white video have generally been conducted because it was easier and less expensive to produce and distribute black-and-white materials. Those limitations have been removed, and, as the authors stated, BAILENSON et al. (2003) found that participants behaved similarly with respect to personal space in VR and physical space. With advances in the virtual landscape, it is now possible to provide a truly colorless, interactive space for users for the first time. This allows designers and researchers to explore how the absence of chromatic information shapes perception, emotion, and spatial understanding. This possibility extends beyond simulation; it opens an entirely new medium for design in which perceptual variables can be isolated, controlled, and redefined. In landscape architecture, virtual landscapes are increasingly utilized for immersive visualization prior to construction, scenario testing, and participatory design. They provide designers the opportunity to observe controlled behavioral reactions that are difficult to isolate in physical environments. Therefore, researching perceptual factors, like color, helps in improving user response interpretation and informing design choices. As such, colorless virtual landscapes hold the potential to become a new design field and methodolog-

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ical framework for future landscape architects who will act in the world of virtual environments, developing new forms to understand and design experiential qualities that transcend the boundaries of physical space (PAN et al. 2018, LATOSCHIK et al. 2019). In terms of information processing, distinctions between colored and monochrome environments can be understood as artifacts of information availability: colored environments provide multiple perceptual channels, whereas monochrome environments limit perceptual input to a single channel (KAPLAN et al. 1989).

This research compared color and monochrome virtual environments to determine their effects on human interaction and spatial behavior. If the impact of monochrome virtual landscapes on human interaction is understood, future landscape architects can use these findings to maximize or minimize user interaction in such landscapes. The results were then interpreted to assess how visual conditions influence proxemic behavior and to provide guidance for applying proxemics theory in virtual, non-physical contexts.

2 Reference Study

This research builds on a body of research from proxemics, psychology, and virtual reality. Each reference contributed in a specific way to the design and direction of the experiment.

Four areas of interpersonal distance are identified by HALL's (1966) proxemic theory: intimate, personal, social, and public. Each of these zones indicates a different level of comfort and involvement. Although his theory was grounded in physical space, the categories he articulated continue to influence discussions of proxemics. This research applies his framework to a virtual landscape and examines how the theory might be affected by changes in visual conditions in VR.

KIM & SUNG (2024) questioned whether HALL's proxemics theory of physical space (1966) can be applied or adapted to virtual landscapes. They observed that proxemic values in virtual landscapes differ from those in physical spaces, which informed this research's selection of a natural environment as the base virtual landscape to examine further how such spatial variations occur under different visual conditions. Their work also emphasized the need to test proxemics under various conditions, which guided this paper's focus on the impact of color on interpersonal interaction. BAILENSON et al. (2003) demonstrated that participants maintain interpersonal distances in VR that are similar to those in physical environments. Their study informed this research, which assumes that proxemic data collected in VR are comparable to behavior in physical space. At the same time, their reliance on physical space underscored the need for further testing under controlled conditions, such as with color filters, which our research addresses.

The understanding of color perception was based on findings from psychological research. BOYATZIS & VARGHESE (1994) observed that children associate different emotions with colors, for instance, yellow with happiness, and blue with sadness or calmness. Their findings indicate that color conveys sensory information that may affect emotional perception of settings, providing a basis for investigating whether color similarly influences sensory behavior and interpersonal interaction in virtual landscapes. ELLIOTT & MAIER (2014) extended this logic to adult psychological functioning; for instance, warm colors such as red can increase focus. In contrast, cool colors such as blue are associated with calmness, underscoring that

color can directly affect mood and behavior. Together, these studies suggested that color changes may affect users' behavior and willingness to engage with virtual landscapes.

SLATER et al. (2000) showed that technical design choices in VR, such as movement techniques (e. g., walking versus controller-based navigation) and smooth motion versus teleportation, affect the sense of presence, with more natural interaction conditions leading to higher immersion and more realistic behavioral responses. This highlighted the importance of controlling the experimental environment and procedures to avoid unintended effects.

3 Methodology

Twenty-five volunteers aged 20-27 participated in the experiment. Before inclusion, all candidates completed a health-screening form; individuals reporting epilepsy, panic disorder, or other conditions that might create risks in virtual landscapes were excluded. Eligible participants then completed the Ishihara Color Vision Test, used to identify red-green color vision deficiencies, the most common form likely to affect digital color perception. The Ishihara test provides a standardized, noninvasive verification method widely used in perceptual research (BIRCH 2001, BARBUR 2018). 25 participants who were tested and passed were admitted. To minimize perceptual variability due to experimental conditions and to enable a controlled comparison between fully chromatic and entirely monochrome virtual landscapes, participants with color vision deficiency were excluded. All gave written informed consent and were assigned numerical codes to preserve anonymity.

The experiment was conducted in a controlled laboratory environment (Figure 1). A fixed position on the floor was marked for participants, who were instructed to remain within this area for safety and consistency. A facilitator monitored each session, provided instructions, and paused or ended trials if discomfort occurred (Figure 2).

Fig. 1: Physical setup for the VR experiment

Fig. 2: Interaction with the VR system

The purpose of the experiment was to minimize uncontrollable factors that could affect distance while preserving perception. Instead of walking or being affected by others walking patterns, participants used a handheld controller to adjust their distance to ensure accurate, repeatable, and comparable lengths. To verify that the changes in interpersonal distance resulted from participants' perceptual management rather than merely from responses to a moving avatar, the avatar remained constant throughout the experiment. To provide a social en-

vironment and ensure that changes in interpersonal distance occurred within the interactional setting, vocal interaction was maintained throughout the experiment.

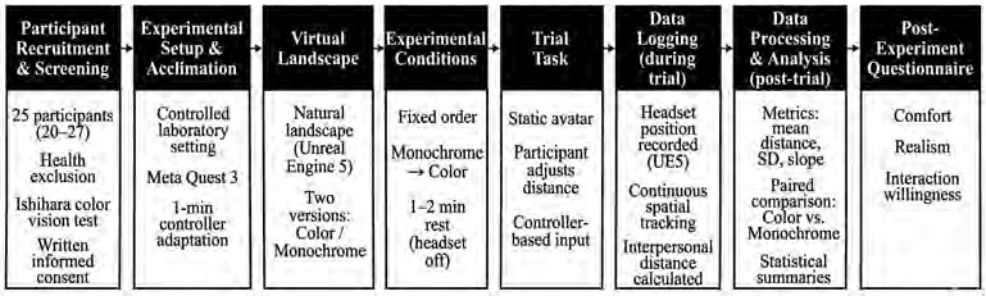

Fig. 3: Experimental procedure

The virtual landscape was designed to resemble a natural environment, consistent with evidence that natural settings are most suitable for proxemic studies in virtual landscapes (KIM & SUNG 2024). Two identical versions were created in Unreal Engine 5: one rendered in monochrome grayscale, which converts RGB color values to luminance-based grayscale (Figure 4), and the other in full natural color (Figure 5). To ensure consistency, the same grayscale conversion method was applied throughout the virtual landscape, with no additional contrast or tonal adjustments. Except for the color filter, all parameters, including geometry, textures, scale, lighting, and avatar placement, remained constant. The environment was rendered wirelessly via a Meta Quest 3 headset, with Unreal Engine simultaneously managing scene rendering and spatial data logging at one-second intervals.

Fig. 4: Monochrome virtual landscape

Fig. 5: Colored virtual landscape

Each participant interacted with a human anchor who stood still in the physical room, reading neutral, pre-recorded questions adapted from KIM & SUNG (2024) was made because proxemic behavior can be studied independently due to their verbally neutral questioning protocol, which is specifically made to keep participants engaged while preventing linguistic, emotional, or social cues from influencing interpersonal distance. The same human anchor was represented by a static, neutral-gray avatar in the virtual landscape (Figure 6) positioned directly opposite the participant. The avatar did not move or speak; only the anchor in the physical world provided voice auditory interaction.

Fig. 6: Anchor in the virtual landscape

A one-minute adaptation phase preceded data collection, during which participants practiced forward and backward movement using a handheld controller, their only way of moving in the virtual landscape. This familiarization minimized the influence of inexperience with the equipment and the experiment.

The experimental procedure (Figure 3) included participant preparation, environmental familiarization, the main experimental phase, and data review and analysis. During the adaptation phase, participants familiarized themselves with the setup and practiced using the controller for two to five minutes to ensure technical comfort. Throughout each trial, participants remained in a designated position, facing the avatar, adjusting their virtual distance using the controller to suit their comfort. Unreal Engine automatically logged positional data to compute real-time interpersonal distances.

Following adaptation, participants completed two experimental sessions, each approximately two to three minutes. The order was monochrome first, then color, to reduce potential bias, as prior exposure to richer visual information could influence perception in the monochrome condition. This approach was intended to minimize potential influence from prior visual exposure rather than to establish a baseline condition. Between sessions, the headset was removed for a one- to two-minute rest to prevent visual fatigue, consistent with recommendations by STANNEY et al. (1997) and GAVGANI et al. (2017). During each session, participants faced the avatar and answered questions aloud while adjusting their virtual distance using the controller to maintain a comfortable interpersonal distance (Figure 8). Unreal Engine continuously recorded headset position and computed Euclidean distance to the avatar's root node, producing a time-series dataset for each condition.

To ensure measurement accuracy, all positional data were synchronized with system timestamps and verified for frame consistency. Minor tracking losses were automatically interpolated by Unreal Engine's internal smoothing function, ensuring continuity in the distance record. Participants were instructed to rely only on visual and auditory cues; no physical motion feedback or hand tracking was enabled to isolate the perceptual influence of visual conditions. Each movement input through the controller corresponded to a linear translation along the Z-axis, calibrated at a constant rate to maintain uniform movement sensitivity between trials. For observed behavioral variance to more likely reflect perceptual or cognitive differences, this setting was designed to reduce technical differences.

Immediately after each session, participants completed a questionnaire (Table 1) to capture their responses while the experience was still recent. The form contained five-point Likert-

scale questions assessing comfort level, virtual landscape realism, willingness to engage, and responsiveness, as well as open-ended questions on perceived proximity to the avatar and time estimation. Responses were coded by condition to enable direct comparison.

Table 1: Post experiment questionnaire

How comfortable did you feel during the walk/scene? (1–5)	How close or distant did the person in front of you feel? (m-cm)	How realistic did the colors feel to you? (1–5)
How long do you think the experience lasted? (sec-min)	How strong was your desire to respond to what was being said? (1–5)	Would you have liked to interact with the person in front of you? (1–5)

From the logged data, three primary metrics were computed: mean interpersonal distance, within-session standard deviation, and the slope of distance change over time. Within-session standard deviation quantified the frequency of distance changes within a session and the consistency with which participants maintained their positions. The rate of change and direction of participants' interpersonal distance from the avatar over time are indicated by the slope; the slope is highlighted when participants increase or decrease their interpersonal distance from the avatar. Samples affected by brief tracking interruptions were excluded, and sessions with technical errors were repeated. Questionnaire data were summarized by condition, and open-ended responses were reviewed to contextualize numerical patterns. Each participant performed a 30-second interpersonal-distance task under both visual conditions, with data collected at 3-second intervals (10 data points per trial). (Table 2) Mean distances, standard deviations, and change rates were computed to evaluate spatial behavior and stability.

All analyses and visualizations were generated in Python using *Pandas* and *Matplotlib*. The analytical framework included paired comparisons, distributional analyses of condition differences, mean-variance correlations, group-level distance trajectories with standard error margins, and participant-specific linear regression slope estimates. This multi-layered analysis revealed subtle variations in spatial consistency between color and monochrome environments while confirming that the mean interpersonal distance remained statistically unchanged across conditions.

Table 2: Time-series interpersonal distance data by participant and visual condition

set No	EXP NO	TARGET CODE	Condition	0s	3s	6s	9s	12s	15s	18s	21s	24s	27s	30s	Average (cm)
1	3	P01	Color	200	276	348	305	500	452	469	469	512	486		**401.7**
1	2	P01	Monochrome	244	200	352	384	416	356	336	312	300	332		**323.2**
2	3	P02	Color	156	156	156	156	156	156	156	156	156	156		**156.0**
2	4	P02	Monochrome	436	436	436	504	520	544	524	524	650	680		**525.4**
3	5	P03	Color	288	288	288	288	320	320	320	320	320	320		**307.2**
3	6	P03	Monochrome	204	204	204	204	204	204	204	204	204	240		**207.6**
4	7	P04	Color	200	216	216	236	236	236	236	236	236	236		**228.4**
4	8	P04	Monochrome	84	40	100	100	124	200	180	220	208	232		**148.8**
5	9	P05	Color	236	204	236	236	196	196	196	220	240	212		**217.2**
5	10	P05	Monochrome	108	108	108	108	108	108	108	116	112	112		**109.6**
23	45	P23	Color	128	128	128	128	128	128	128	128	128	128		**128.0**
23	46	P23	Monochrome	108	108	108	84	112	100	120	120	120	120		**110.0**
24	47	P24	Color	320	284	284	284	284	284	284	284	284	284		**287.6**
24	48	P24	Monochrome	108	108	216	300	208	208	252	132	92	152		**177.6**
25	49	P25	Color	200	200	200	200	200	200	200	200	200	200		**200.0**
25	50	P25	Monochrome	200	200	256	272	272	272	240	192	192	236		**233.2**

4 Results

The quantitative results demonstrate that while color exerts a measurable influence on behavioral consistency and spatial control stability, it does not significantly affect the average interpersonal distance between participants and the non-player character (NPC). Across all six figures, the mean distances recorded in color and monochrome conditions were nearly identical ($\Delta \approx 3$ units, $p > .8$), as illustrated in Figures 7 and 8. The paired difference distribution was symmetrically centered at zero, indicating the absence of a systematic bias toward either visual condition. A single extreme outlier accounted for a minor variance deviation but did not alter the overall interpretation of the dataset.

A secondary pattern emerged in Figures 9 and 10: variability in distance increased significantly under monochrome conditions. Participants exposed to the monochrome environment showed greater variance and higher within-subject standard deviations. In contrast, those in the color condition exhibited more tightly clustered data, suggesting greater spatial consistency. This pattern indicates that color contributes to perceptual stability, improving users' ability to regulate and maintain interpersonal distance with reduced fluctuation.

Temporal analyses, presented in Figure 11, further support this observation. Although both groups gradually increased their distance from the NPC over time, the monochrome condition exhibited a larger standard error of the mean (SEM), indicating greater variability among participants. The mean trajectory remained parallel across both conditions, suggesting that color removal affects interaction stability rather than comfort or approach behavior.

Finally, the slope analysis in Figure 12 revealed a weak trend toward gradual disengagement in the monochrome condition (+2.9 vs. +1.8 units per 3 s), yet the difference was not statistically significant. The majority of slopes clustered near zero, indicating overall behavioral stability. Collectively, these findings confirm that color enhances the precision and steadiness of social movement rather than modifying the fundamental interpersonal distance preference. No further analysis was conducted to investigate interactions between mean interpersonal distance and demographic characteristics, as the experiment was not designed for subgroup comparisons.

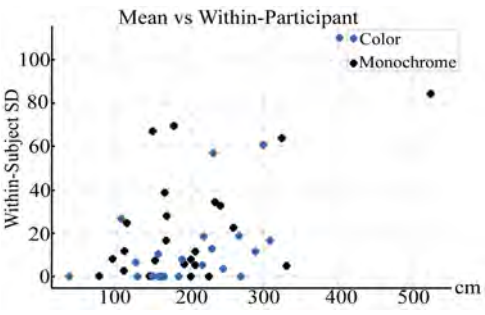

Fig. 7: Mean vs. Within-participant

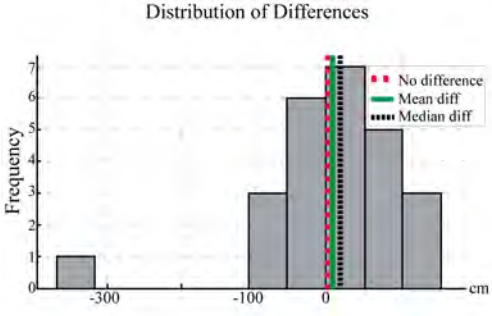

Fig. 8: Distribution of differences

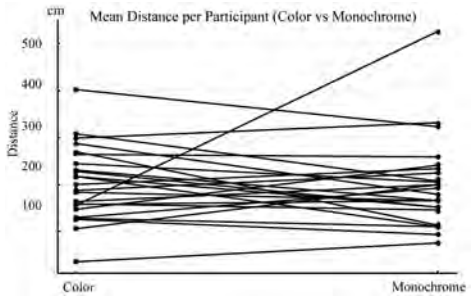

Fig. 9: Mean distance per participant

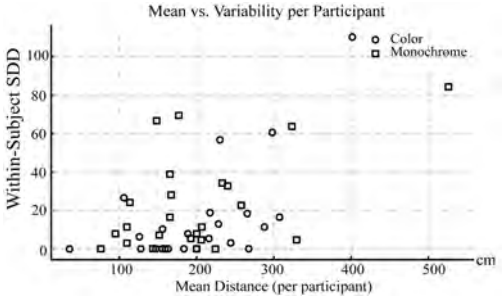

Fig. 10: Mean variability per participant

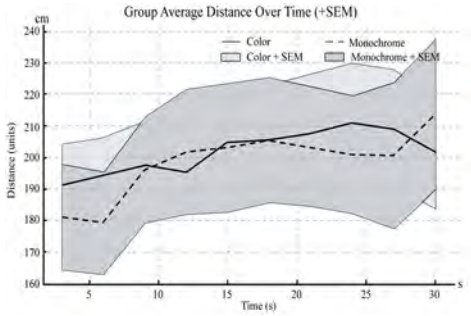

Fig. 11: Group average distance over time

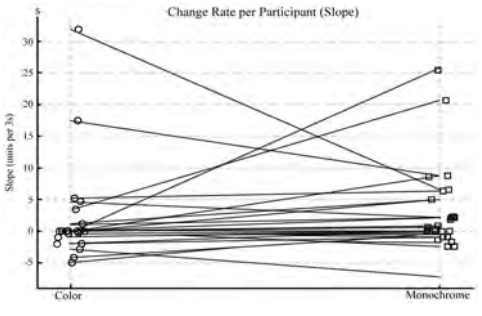

Fig. 12: Change rate per participant

5 Discussion

Previous research on virtual proxemics has been mainly conducted to examine whether people's interpersonal distance preferences are similar between the physical and virtual environments or how the richness of visuals would enhance presence and realism (HALL 1966, BAILENSON et al. 2003, SLATER et al. 2000, KIM & SUNG 2024). In many of these studies, distance serves as a static element of comfort or social intention. The present results contribute to the study of virtual landscapes by showing that desired interpersonal distance stability depends on the visual context rather than on actual distance. Across both colorful and monochromatic environments, the average interpersonal distance did not change. Still, significantly greater variation in participants' spatial management behavior was observed under fewer constraints when color was removed from the environment. The greater variation observed in monochrome environments indicates that the absence of chromatic information weakens perceptual stability and results in less stable spatial behavior. More consistent behavior is supported by visual richness, whereas environments with fewer cues might help indicate spatial control. These results suggest that visual circumstances may be modified based on whether the goal is perceptual stability or exploratory observation. The fixed presentation order should be considered when interpreting the results, as potential order effects cannot be fully ruled out.

6 Conclusion

The research concludes that visual conditions function as a stabilizing factor in social virtual environments. The presence of color enhances perceptual clarity and behavioral consistency without altering comfort-based interpersonal interactions. Presenting environments in monochrome only results in greater variability and less predictable motion, suggesting that users experience diminished perceptual certainty rather than changes in preferred spacing. Thus, color operates as a perceptual anchor, supporting steadier self-positioning and interaction control in immersive contexts.

These findings align with previous research emphasizing the psychological and perceptual roles of color. ELLIOTT & MAIER (2014) demonstrated that color can influence emotional regulation and attentional focus, while SLATER et al. (2000) associated multisensory richness with an enhanced sense of presence in virtual environments. The present research extends this theoretical framework by providing experimental evidence that color contributes to interaction stability and confidence in maintaining controlled interpersonal behavior within virtual landscapes.

For landscape architecture, these results are relevant to the field's involvement in the creation of virtual and hybrid landscapes. Understanding how factors such as color influence interpersonal distances and behavior is crucial as landscape architects engage with virtual landscapes through participatory design, education, and spatial understanding. These results indicate that social behavior in virtual landscapes is influenced by visual conditions, which should be considered active design factors rather than only representational elements. The study examined how visual conditions shape spatial experience by clarifying how color affects the stability of interpersonal interaction.

However, this research was limited to a single virtual environment and a binary color comparison. Future research could explore a broader spectrum of colored environments, including variations in hue, saturation, and brightness, to determine which configurations best facilitate emotional comfort and social balance. Furthermore, expanding the participant selection to include individuals with color vision deficiencies could reveal how perceptual diversity shapes spatial behavior in virtual landscapes. Such investigations could deepen the understanding of color-oriented interaction mechanisms and support the development of emotionally supportive and perceptually stable virtual landscapes.

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Seating Configuration, Visual Attention, and Perceived Social Affordances in Urban Greenways

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Abstract: Urban greenways support social life through localized gathering nodes, where furniture configuration influences navigation and social interaction affordances. This study examines how seating configurations shape visual attention, exploratory behavior, and perceived social interaction in greenway gathering spaces, while accounting for individual differences in perceived social support. A within-subjects VR experiment exposed participants to three environments differing only in seating configuration: sociopetal, sociofugal, and mixed. Eye-tracking measured visual attention to seating elements, and movement data assessed exploratory behavior. Perceived social support was measured using the Multidimensional Scale of Perceived Social Support, and social interaction affordances were evaluated through post-exposure questionnaires. Seating configuration was associated with differences in visual attention and perceived social interaction, with the sociopetal configuration receiving higher social engagement ratings and the sociofugal configuration eliciting higher visual attention to seating, particularly among participants with lower perceived social support. No significant differences were observed in overall movement extent, though navigation patterns varied spatially. These findings highlight seating configuration as a meaningful design variable shaping how greenway gathering spaces are visually attended to and socially perceived.

Keywords: Urban greenways, urban furniture, virtual reality (VR), eye-tracking, social affordances

1 Introduction

Urban greenways are key components of urban green infrastructure, supporting transportation, recreation, environmental performance, and social life (HORTE & EISENMAN 2020). Although often framed around connectivity and movement, their social value is shaped less by the corridor as a whole than by localized gathering nodes where people slow down, linger, and encounter others. Within the framework of social infrastructure, these nodes provide conditions for interaction, but do not guarantee it. Social life in public space is mediated by design (WHYTE 1980). In greenways, small-scale interventions, particularly urban furniture configurations, play a decisive role in shaping how spaces are used, who feels welcome, and which forms of interaction are encouraged or constrained.

Urban furniture functions as an affordance system that structures how gathering spaces are perceived and occupied. By shaping orientation, proximity, and opportunities for lingering, furniture configurations bias the range of possible actions and interactions. Orientation and spacing influence whether users engage in passive observation, parallel use, or direct social exchange, while flexibility versus fixity conditions how people adapt spaces to their needs (WHYTE 1980). A central distinction in public space design is between sociopetal configurations, which orient users toward one another and facilitate interaction, and sociofugal configurations, which emphasize separation or privacy (HALL 1966). While sociopetal and sociofu-

Journal of Digital Landscape Architecture, 11-2026, pp. 975-983. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-770-0, ISSN 2367-4253, doi:10.14627/537770092.

gal furniture configurations structure opportunities for social interaction, their effects may not be uniform across users. Research on personal space demonstrates substantial individual variation in tolerance for interpersonal proximity (SOMMER 1969). Perceived social support similarly reflects stable differences in comfort with and expectations of social relationships (ZIMET et al. 1988), suggesting that spatial affordances may be interpreted differently across individuals. As a result, identical furniture configurations can elicit divergent social behaviors, particularly in semi-public, transitional spaces such as greenways where interaction norms are ambiguous. These dynamics underscore the importance of incorporating individual-level variables into analyses of social node design.

Existing research on public space and furniture design has largely relied on observational and self-report methods to document real-world use patterns, social behaviors, and lived experience (ASKARIZAD & HE 2025, MEHTA & BOSSON 2021). These field-based approaches offer high ecological validity and capture the complexity of naturally occurring social interactions. However, because design variables co-vary in real settings, isolating the effects of specific furniture configurations remains challenging, and cross-site comparisons are often influenced by uncontrolled contextual factors such as weather, surrounding activity, and temporal variation.

Controlled experimental environments provide a complementary approach for addressing these limitations. Virtual reality (VR) enables systematic manipulation of design variables while holding environmental context constant, allowing experimental testing of configuration effects that are difficult to examine in situ. When paired with eye-tracking and movement tracking, VR supports objective measurement of visual attention and exploratory behavior. Movement monitoring has proven to be an effective approach across multiple disciplines for the analysis of human behavior (FATTAHI et al. 2024). Prior research indicates that exploratory navigation in virtual environments is comparable to real-world settings, supporting VR as a valid extension of established public-space research methods (ZACHARIAS 2006).

Building on prior work, this study uses VR-based eye tracking to examine how urban furniture configurations shape visual attention and exploratory behavior in greenway gathering spaces. By isolating furniture configuration, it provides empirical evidence linking design decisions to social affordances in urban greenways. The study addresses four research questions: (RQ1) How do different urban furniture configurations influence visual attention within greenway gathering spaces?, (RQ2) How do furniture configurations affect exploratory behavior during navigation in a virtual greenway?, (RQ3) How do individual differences in perceived social support relate to visual attention and exploratory behavior across furniture configurations?, (RQ4) How do furniture configurations influence perceived social interaction affordances, and which seating attributes are perceived as most important for supporting social use in greenway gathering spaces?

2 Methods

2.1 Study Design and Participants

This study used a within-subjects experimental design to examine how urban furniture configurations influence visual attention and exploratory behavior in a virtual urban greenway. Each participant experienced three virtual environments depicting the same greenway setting. Environmental variables, including square footage, materials, color palette, vegetation, light-

ing, and surrounding hardscape, were held constant across conditions; only the spatial configuration of seating was manipulated. The three seating configurations represented distinct social orientations in public space design: sociopetal, sociofugal, and a mixed configuration. This design isolated the effects of furniture configuration while minimizing environmental confounds.

Fifteen participants were included in the final analysis. Participants ranged in age from 26 to 52 years; 70% identified as male and 30% as female, 80% reported prior virtual reality experience, and participants reported a high level of comfort navigating the virtual reality VR environment ($M = 4.29$, $SD = 0.77$). Participants were recruited via flyers, were over 18, and were able to participate without wearing glasses. An initial pilot experiment with six participants assessed instruction clarity, virtual environment usability, and survey items. Minor protocol revisions followed, and pilot data were excluded from final analyses. Participants received a $10 gift card. All study procedures were approved by the UW-Madison Institutional Review Board (IRB #2025-1047), and informed consent was obtained prior to participation.

2.2 Measures

Visual attention was assessed using eye-tracking data collected continuously during each virtual environment exposure. Areas of interest were defined a priori and included seating elements, circulation paths, vegetation, and surrounding hardscape. The eye-tracking metric was fixation duration, which measures sustained visual engagement. Exploratory behavior was operationalized using path length (total distance traveled between teleportation points) and teleportation point count (number of locations visited per environment). Perceived social support was assessed using the Multidimensional Scale of Perceived Social Support (MSPSS), a validated 12-item self-report measure of perceived support from significant others, family, and friends (ZIMET et al. 1988). Items are rated on a 7-point Likert scale, with higher scores indicating greater perceived support. The MSPSS was administered prior to VR exposure to capture baseline social predispositions and was treated as a moderator variable, reflecting the premise that users bring existing social traits and interaction tendencies into public space. Perceived social interaction affordances were assessed using a post-experiment 5-point Likert-scale questionnaire. Participants rated each setting on multiple social dimensions, including perceived interaction with others, suitability for group interaction, feelings of inclusion or belonging, likelihood of recommending the setting to their community, and preference for solitary use. Perceived importance of seating attributes was assessed by participant ratings of seating features supporting social use in greenway gathering spaces (arrangement, comfort, accessibility, flexibility, lighting, privacy, and vegetation), with optional open-ended comments.

2.3 Virtual Environment and Eye-Tracking Setup

The virtual environments were developed in Unity using assets from the Unity Store (Unity Technologies 2024). Four scenes were used: one calibration scene (S0), in which participants practiced navigation using the joystick and tested the eye-tracking calibration by fixating on cubes, and three urban park scenes (S1-S3; Figure 1), each differing only in furniture configuration. Furniture elements were modeled in Rhino (ROBERT MCNEEL & ASSOCIATES 2024).

To approximate real-world scale, the virtual park covered a 100 × 100 m area and included trees, varied ground textures, and smaller environmental elements such as shrubs and stones.

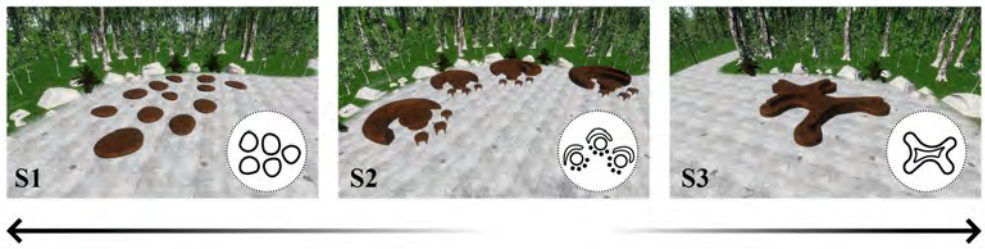

Fig. 1: Furniture configurations in the VR scenes, categorized by social interaction affordances; Sociofugal (S1), Sociopetal (S2), and Mixed (S3)

Participant movement was enabled using a teleportation system. Users held the joystick forward to activate a teleportation ray, which snapped to nearby predefined floor targets. Releasing the joystick moved the user to the selected location, with a brief fade-in/fade-out transition applied to reduce motion sickness. Eye tracking was implemented using the Oculus Android Package Kit. (META PLATFORMS 2024). Data recording began at software launch and continued until the session was terminated by the researchers. The system recorded timestamps and fixation durations whenever participants looked at objects including the sky, trees, and furniture. If calibration issues were identified in S0, the session was restarted to ensure reliable eye-tracking data.

2.4 Procedure

Upon arrival, participants were briefed on study procedures, provided informed consent, and completed a brief demographic questionnaire and the MSPSS. They were then fitted with a Meta Quest Pro head-mounted display, completed the S0 practice session, and freely explored S1-S3 in randomized order for two minutes each before the researcher asked them to proceed to the next condition. Finally, participants completed a post-exposure survey assessing seating perceptions and overall experience.

3 Results

To address the research questions, visual attention was analyzed using eye-tracking–derived fixation metrics compared across furniture configurations (RQ1), and exploratory behavior was assessed using path length and teleportation points within the virtual environments (RQ2). Associations with individual differences in perceived social support were examined using correlation, repeated-measures ANOVA, and linear mixed-effects modeling (RQ3). Perceived social interaction affordances were evaluated using post-experiment Likert-scale ratings and open-ended responses, with differences across configurations analyzed using paired-samples t-tests (RQ4). All statistical analyses were conducted in R with an alpha level of 0.05 (R CORE TEAM 2025).

3.1 Effects of Furniture Configuration on Visual Attention

Visual attention was calculated as fixations on furniture divided by fixations on other scene objects. A repeated-measures ANOVA revealed a significant effect of furniture configuration on visual attention to sitting areas ($p < 0.001$). Post-hoc pairwise comparisons with Bonferroni correction indicated that S2 (M = 0.295, SD = 0.16) elicited significantly higher visual attention compared to S1 (M = 0.122, SD = 0.12), with $p = 0.005$. Although S3 (M = 0.216, SD = 0.12) also attracted more attention than S1, this difference approached but did not reach statistical significance ($p = 0.060$). Finally, no significant difference was observed between S2 and S3 ($p = 0.235$).

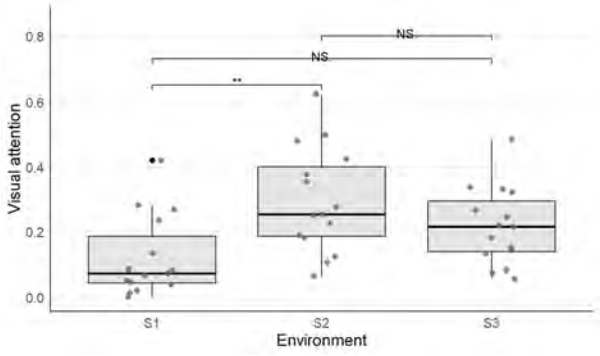

Fig. 2: The effect of furniture configuration on visual attention

3.2 Effects of Furniture Configuration on Exploratory Behavior

Spatial movement patterns varied by furniture configuration, based on visual assessment of Python-generated density heat maps of participant navigation (Figure 3) (MATPLOTLIB DEVELOPMENT TEAM 2024). Visitation in S3 was more spatially distributed along the perimeter, whereas S1 and S2 were concentrated around central seating areas. Path length showed a similar pattern, with the longest average distance in S3 (M = 149.23), followed by S1 (M = 122.86) and S2 (M = 107.17); however, a repeated-measures ANOVA found no significant differences across environments ($p > .05$).

3.3 Perceived Social Support, Visual Attention, and Exploratory Behavior

Building on the configuration effects identified in Section 3.1, Pearson correlations examined associations between MSPSS scores and visual attention within each configuration (Figure 4). Perceived social support was moderately negatively correlated with visual attention in S1 ($r = -0.53$), whereas associations were weak in S2 ($r = -0.12$) and negligible in S3 ($r = -0.002$).

A linear mixed-effects model tested whether MSPSS moderated the relationship between furniture configuration and path length. No significant configuration × MSPSS interactions were observed (S1: $p = 0.556$; S2: $p = 0.891$; S3: $p = 0.428$), indicating that configuration effects on exploratory behavior did not vary with perceived social support.

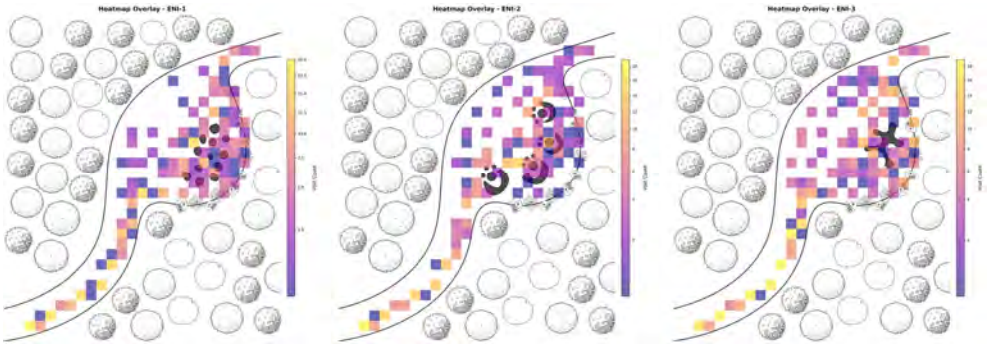

Fig. 3: Density heat maps showing visit counts for participant navigation. Warmer colors indicate higher visitation frequency.

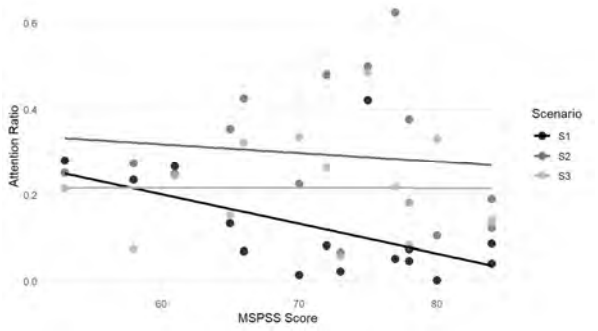

Fig. 4: Relationship between MSPSS scores and visual attention

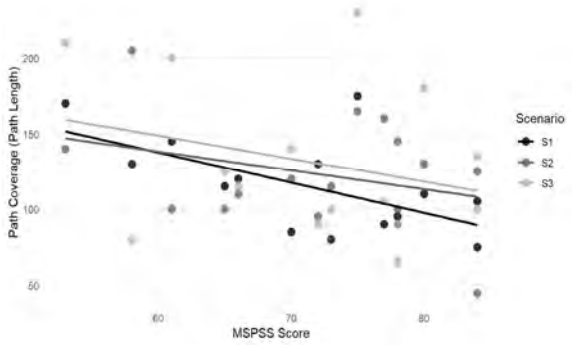

Fig. 5: Relationship between MSPSS scores and path length

3.4 Perceived Social Interaction Affordances and Seating Attributes

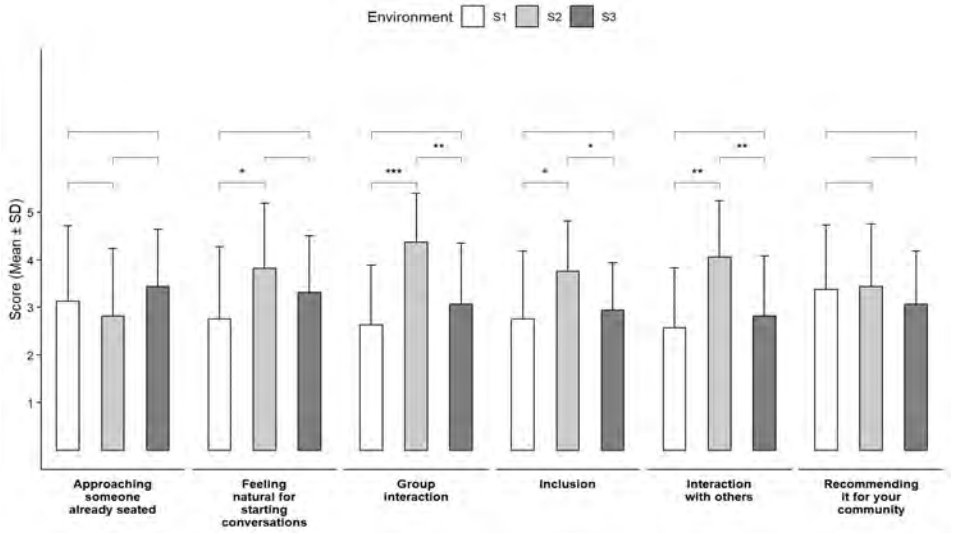

Fig. 6: Perceived social interaction affordances

Results from the 5-point Likert questionnaire showed that S2 consistently received the highest ratings for social engagement. Paired-samples t-tests indicated that S2 significantly outperformed both S1 and S3 on all key social interaction measures. Participants reported higher *Interaction with Others* in S2 (M=4.06) than in S1 (M=2.56, p=.009) and S3 (M=2.81, p=.016). *Group Interaction* was also highest in S2 (M=4.38), with a strong improvement over S1 (M=2.62, p<.001) and a significant difference from S3 (M=3.06, p=.024). Perceived *Inclusion* followed the same pattern, with S2 (M=3.75) rated higher than S1 (M=2.75, p=.037) and S3 (M=2.94, p=.038). No significant differences were observed for the remaining affordances, although *Feeling Natural* showed a marginal trend favoring S2 (p=.084).

Participants identified seating arrangement (M=4.53, SD=0.51), comfort (M=4.43, SD=0.72), and accessibility (M=4.43, SD=0.51) as the most important attributes for supporting social use in greenway gathering spaces, with flexibility, lighting, privacy, and surrounding vegetation also rated as influential. Open-ended responses indicated that each seating configuration supported distinct social experiences: the sociofugal layout was seen as less conducive to group interaction due to scattered seating that created isolated "islands," but its open and flexible spacing lowered social barriers and made it easier to approach others; the sociopetal configuration was most strongly associated with group interaction and inclusion, as circular seating and tables oriented users face-to-face and encouraged shared activities, creating a communal atmosphere; and the mixed configuration supported gradual, low-pressure interaction by balancing privacy and connection through natural seating distances and semi-enclosed areas that allowed users to engage at their own pace.

4 Discussion

This study examined how urban furniture configurations in greenway gathering spaces shape visual attention, exploratory behavior, and perceived social interaction affordances using a controlled VR eye-tracking experiment. By isolating seating layout while holding environmental context constant, this study provides evidence that configurational design decisions directly influence how users perceive, interpret, and engage with social spaces.

Across conditions, furniture configuration significantly shaped visual attention. Qualitative responses clarify that the sociofugal configuration (S1) was perceived as visually open but socially ambiguous; this lack of clear interaction cues prompted increased visual scanning, particularly among individuals with lower perceived social support. In contrast, the sociopetal configuration (S2) was immediately legible, with circular seating clearly signaling group interaction. Consequently, S2 received the highest ratings across all social engagement measures (Interaction with Others, Group Interaction, and Perceived Inclusion). In S2, visual attention was lower and independent of perceived social support, suggesting that clear spatial affordances reduce the need for constant social assessment. The mixed configuration (S3) functioned as a middle ground, supporting gradual, low-pressure interaction. While individual social traits did not dictate overall movement quantity, navigation heat maps reveal that furniture arrangement systematically influenced the spatial distribution of exploration.

These patterns suggest that seating configuration plays a primary role in shaping the greenway experience. While this study examines perceived social interaction affordances rather than enacted social behavior, this distinction is important. The VR and eye-tracking methods capture attentional and exploratory processes that precede and potentially shape social engagement, but they do not measure actual interpersonal interaction. The findings therefore speak to how seating configurations structure visual attention and perceived social possibilities, rather than confirming social interaction outcomes. Future research integrating observational data or use of avatars in VR would be valuable for examining how these perceptual patterns translate into realized social interactions within greenway environments.

Several limitations should be noted. The modest sample size limits generalizability, and the use of teleportation points constrains the interpretation of natural movement. Furthermore, factors such as furniture volume and visual complexity were not explicitly controlled and may have influenced visual attention. Future studies should replicate these findings with larger, more diverse samples and incorporate physiological measures (e. g., heart rate variability or electrodermal activity) alongside high-fidelity 3D models to better capture the cognitive and emotional nuances of social spatial design.

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A Multi-Faceted Technological Approach to Citizen Participation: The Dundrum by Design Initiative

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Abstract: Technological approaches in urban planning processes can offer long-term benefits, including citizens empowered to co-design their towns, increasing the likelihood of public project approval, and a variety of solutions tailored to a town's needs, such as general climate adaptation. Ireland has been slow to adopt digital technologies in the non-statutory phases of urban planning, limiting itself to rigid, bureaucratic statutory processes. Dundrum by Design is presented as an innovative case study that aims to bridge the gap between local authority, communities, pedagogy and technology. Using semi-interoperable design platforms, Dundrum by Design broadens the public's accessibility towards participation in these crucial early stages. Community inputs have created a substantial database for the local authority and the Dundrum Living Street scheme, advancing conversations in each phase as the initiative progresses. Our findings show the initiative's gradual public acceptance and increasing community uptake, results likely derived from the transparency of digital tools used and the relationships built with community groups. The initiative's results aim to equip the local authority with data-backed solutions, sensitive to the local community's needs and to climate adaptation, while also providing technology-based capacity building for future schemes.

Keywords: Geodesign, climate simulation, community engagement, digital tools

1 Introduction

For decades, urban planning has been slow to address the technological gap between meaningful citizen participation and urban design processes (HUDSON-SMITH & SHAKERI 2022, SONDOU et al. 2025). As society becomes increasingly urbanised and digitally advanced, an additional need is placed on methods that promote a just, people-centred, climate transition (TURILAZZI et al. 2021, KAVOURAS et al. 2025). Meanwhile, histories of top-down approaches and a lack of transparency result in low trust and little community participation (ARNSTEIN 1969, GABER 2019). Research indicates that supporting community co-participation, co-design, and co-creation in early urban design discourses can facilitate the growth of green, sustainable neighbourhoods (BUIJIS et al. 2024, KAVOURAS et al. 2025). Moreover, the use of technology further promotes transparency and a holistic picture of the future (LIN 2022, OH & RYDIN 2025).

In this context, the 2025 Dundrum by Design initiative (DbD) is introduced as a case study that utilises innovative methods and digital platforms to bring local voices into design deci-

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sions that aspire to shape the future of Dundrum.[1] As an ongoing collaboration between University College Dublin (UCD) School of Architecture, Planning and Environmental Policy, Dún Laoghaire-Rathdown County Council (DLR), and the Dundrum community, it is framed within the EU-funded PROBONO project. DbD adopts the Living Lab approach (VOYTENKO et al. 2016) to combine state-of-the-art technical and social innovations for the climate transition. It also takes a pedagogical approach, involving UCD Architecture students in climate-sensitive, real-world problem-solving with the community, co-developing collective visions for the village while situating proposed interventions within the realities of the current climate context.

Through the PROBONO Dublin Living Lab, DbD provides an opportunity to prototype and evaluate innovative methods and tools, such as the geodesign approach, for engaging a wide range of stakeholders, including local communities, in the green transition process. DbD's focus is on Dundrum's historic streets, particularly Main Street and Taney Cross, which are undergoing significant transformation. These include the redesign of the junction to enhance the pedestrian experience, improving the public realm, and reconnecting with the remainder of the major town centre; the proposed redevelopment of the Old Shopping Centre, featuring a new public park. The Council's vision is to make Dundrum a more pedestrian-friendly village centre with active, inviting public spaces and parks while enhancing its historic character and supporting a vibrant local economy. By employing innovative technologies, DbD encourages stakeholders to flag other areas requiring interventions, supporting a broader range of citizen input. The input collected from the partnership process will be shared with DLR and taken into consideration, particularly for the Dundrum Living Streets project, a scheme focused on promoting sustainable mobility and enhancing the public realm.

DbD's use of multiple semi-interoperable digital platforms intends to diversify early consultation as part of non-statutory processes and provide participation opportunities as the project progresses. These platforms record citizen desires, conduct debriefings, elaborate various climate simulations and integrate community-informed student interventions. Meanwhile, climate simulations equip DLR with contextual climate solutions, based on existing data and future projections. The project also builds on previous geodesign workshops led by UCD (COCCO et al. 2025), incorporating lessons learned and methodologies, whilst in parallel aligning DbD with broader frameworks such as that of the New European Bauhaus.[2] Therefore, when faced with the current challenges of implementing a valuable community-centred technological approach, DbD intends to answer the following questions:

1) How can urban design processes engage diverse stakeholders – local authorities, academic institutions, private enterprises, citizens, and community groups – in a co-design process that incorporates local knowledge and expertise?
2) How can a technological approach substantially benefit all parties involved and provide a starting point for future urban discourses?

[1] Dundrum is a neighbourhood located in Dublin's outer suburb, and it is considered one of the two "Major Town Centres" of the Dún Laoghaire-Rathdown county, part of Dublin County. This study refers to the Dundrum Village as the area defined in the 2023 Dundrum Local Area Plan, encompassing a population of roughly 6,000 as reported in the 2022 census.

[2] https://new-european-bauhaus.europa.eu/index_en

The plan for DbD's activities was methodically set from these questions, as the project aspires to enact the shift towards people-centred planning processes. Where local authorities are bound by slow bureaucratic processes, rigid statutory structures and risk aversion, the case for testing the boundaries of possibility will be further explored in this paper. This paper argues that employing a multi-faceted technological approach in urban design processes helps local authorities boost community engagement and promotes a holistic, systems-thinking overview of Dundrum.

The assessment of digital participatory planning commonly distinguishes between workflow effectiveness, referring to the operational quality of the participatory process, and participation impact, which concerns the extent to which participation influences policy and decision-making outcomes. In relation to the workflow effectiveness, LEE et al. (2022) developed a comprehensive evaluation framework structured around four key dimensions: Feasibility (process viability given resources and capacity), Value (participant perception of worthiness), Change/Action (tangible influence on decisions), and Sustainability (long-term viability). ATAMAN et al. (2025) emphasise that critical success factors for digital participation in dense urban contexts include context-specific interventions, active engagement between residents and designers, integration of multi-scale datasets, and structured evaluation metrics. ATZMANSTORFER et al. (2025) further identified transparent dissemination strategies and active stakeholder engagement mechanisms as essential.

Against this theoretical backdrop, the remainder of the paper examines the methodology adopted to integrate a diverse set of digital tools within the DbD initiative. It then presents the results and data gathered throughout the project, which are subsequently evaluated in the discussion section against the frameworks for assessment outlined above.

2 Methodology

DbD brings together diverse stakeholders in a collaborative process, empowering citizens to take an active role in urban design. The Dundrum by Design workflow (Figure 1) follows a structured, multi-phase process that blends community insight, educational involvement, and digital tools to inform urban design. It begins with groundwork to understand stakeholders and local climate conditions (Preparatory Phase), followed by a Knowledge-Gathering Phase where residents, young people, and students share perspectives through mapping sessions, games, and discussions. The workflow then moves into hands-on workshops that use geodesign methods and tools, school-based gaming activities, and community voting to shape shared proposals (Workshop Phase). In the final stage (Post-Processing Phase), these ideas are refined through climate-focused simulations and compiled into a report that reflects the collective vision, including strong input from young participants.

Three principal digital platforms were used throughout the process to record responses and enable meaningful engagement from the various key stakeholders and the broad Dundrum community, to co-create ideas for a more vibrant, inclusive, and climate-resilient Dundrum village. These platforms, expanded on below, were supported by three official communication channels (website, social media and mailing list) and traditional engagement methods (flyers, posters, displays, public talks, meetings with community groups, etc). When combined, these platforms allow data to flow from the initial Knowledge-Gathering Phase to the final presentation, continuously building on the inputs acquired.

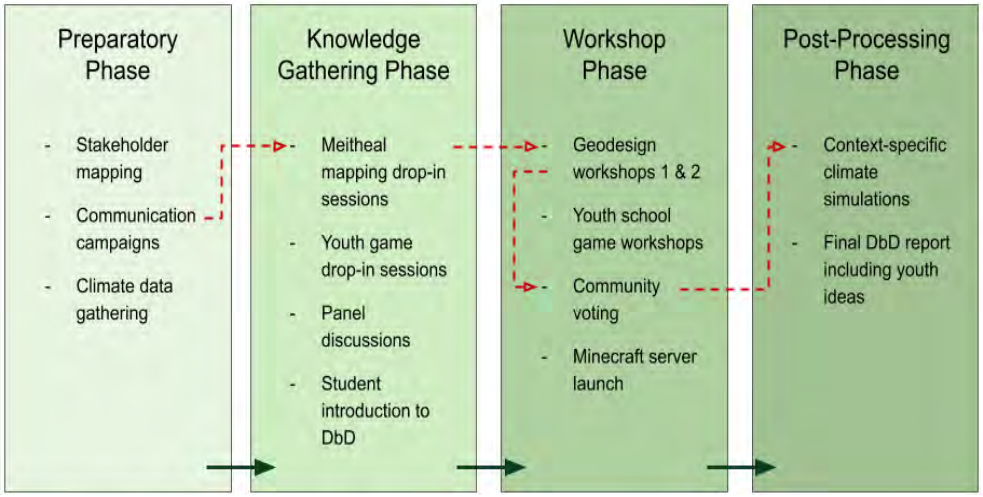

Fig. 1: DbD workflow diagram, including the output pathway between digital platforms highlighted in red

1. *Meitheal* Mapping (powered by CartoSpot) – The first platform used recorded community inputs during the initial project phase. Responses were geolocated on a map of Dundrum using a customised instance of the Cartospot.com geosurvey. The map-based participation platform (KULAWIAK et al. 2023) allowed community members to view inputs made by their neighbours, prior to making their own input. The Dundrum Stories and Values map[3] gathered valuable contextual information, while the Dundrum Challenges[4] and Dundrum Opportunities[5] maps gathered input into 8 territorial systems (Amenity and Public Space, Retail Spaces, Green and Blue Infrastructure, Housing, Active Mobility, Connectivity, Vehicular Mobility and Heritage). Architecture students drew on these inputs as a primary reference to guide their design strategies and interventions, ensuring they reflect the community's perspective. Outputs gathered were recorded on an Excel spreadsheet and were transformed into spatial representations, mapped as polygons on the Geodesign Hub platform in preparation for the geodesign workshop 1.

2. GeodesignHub – The community's input on Meitheal was used as the starting point during the workshop phase. DbD held a first community geodesign workshop[6], using the GeodesignHub.com collaborative tool. The platform allowed community members and students to negotiate preferences and priorities for Dundrum. With the support of facilitators (Master's students), participants divided into 6 stakeholder groups compiled each relevant Meitheal input into an overall map. Groups presented their maps before being joined into two coalitions. During the post-processing phase, two maps were created. The first map highlights shared priorities that both groups agreed upon during the geodesign workshop. The second

[3] https://meitheal.cartospot.com/map/dundrum-stories-and-values/
[4] https://meitheal.cartospot.com/map/dundrum-challenges/
[5] https://meitheal.cartospot.com/map/dundrum-opportunities/
[6] https://storymaps.arcgis.com/stories/54c6fddc4cdf4649875dd9802c8ca899#ref-n-6mS5ik

map, which contains 18 ideas where no consensus was reached, was hosted on DLR's community consultation platform, "Citizen Space," and used for community voting, allowing members of the broader community to express their preferences. The agreements and voting ideas that received between 60% and 100% approval were exported and will be tested across four areas in Dundrum as part of the urban climate simulation (geodesign workshop 2).

3. Minecraft – A combination of digital and analogue serious games was employed to collect input from Dundrum's youth. Minecraft was used as the primary tool to gain children's interest in Dundrum, enabling them to co-create spaces and interventions through their perspective (POPLIN et al. 2022). The tool, an intuitive and attractive method to engage young minds, at times coaxed adults to join. Its use during the early drop-in sessions also supported Meitheal, whereby parents waiting for their children to complete the urban designing activities would complete a minimum of one submission on Meitheal. A live Minecraft server is currently operating to collect youth input from ages 8 to 18, building on 5 school workshops that engaged 160+ students.

4. Urban Climate Change Research Network (UCCRN) Toolkit – To support the climate transition, a separate analysis is ongoing, informed by results from the platforms above. This analysis, led by researchers at the University of Naples, uses GIS and 3D modelling tools to assess climate risks, map urban heat island and flood zones, and quantify co-benefit (RAVEN et al. 2025a,b). Expected outputs include analyses of urban heat islands, projected climate, flood risks and strategies for climate and green interventions. Results from the first geodesign workshop and Meitheal offer a community-driven scenario testing framework, facilitating a contextual assessment of local climate conditions. Simulations, responding to various visions and desires, will be presented and tested at the second community workshop in January 2026. The outcomes will provide a comprehensive toolkit for DLR, relating to policy impact modelling and providing means for informed decision-making.

3 Results and Findings

The results gathered thus far indicate that a multi-platform approach can efficiently organise community inputs, boost local engagement and use general responses to answer specific questions. The preliminary results have confirmed the rise in local uptake of the initiative, providing descriptive metrics in addition to qualitative outcomes from the geodesign workshop and the subsequent analytics from the community voting platform.

Empowering local citizens to become active members in designing their future led to the general adoption of DbD as an initiative advocating for tangible change. As a clear product of this approach, the DbD mailing list rose from 30 registrations in one month to 149 at the time of writing. Similarly, traffic to DbD's official Instagram page increased from 2,000+ views during the first month of its launch[7], to 88,000+ views by the end of October. Pedagogical implications accounted for 16,000+ views for a single post related to a large-scale student-curated event[8] in the community. Furthermore, the first platform used to record citizen inputs, Meitheal, gained approximately 121 ideas across the 8 territorial systems. This

[7] Dates: 30 July – 31 Aug

[8] The event was carried out as part of Open House Dublin, a onfree festival of architecture held across the county. UCD's event in Dundrum can be viewed here:

later rose to 169 individual ideas after the geodesign workshop held in late September (16 community members participated), incorporating student interventions and counting the total community inputs. Although the overall number of ideas was reduced to 92 ideas relating to the Living Streets initiative, the gradual increase and general shift are evident (Figure 2). The community voting page gained a collective 455 votes across 18 Living Streets ideas in one month. Meanwhile, data on Minecraft, where youth engagement is carried out, is currently being collected and analysed.

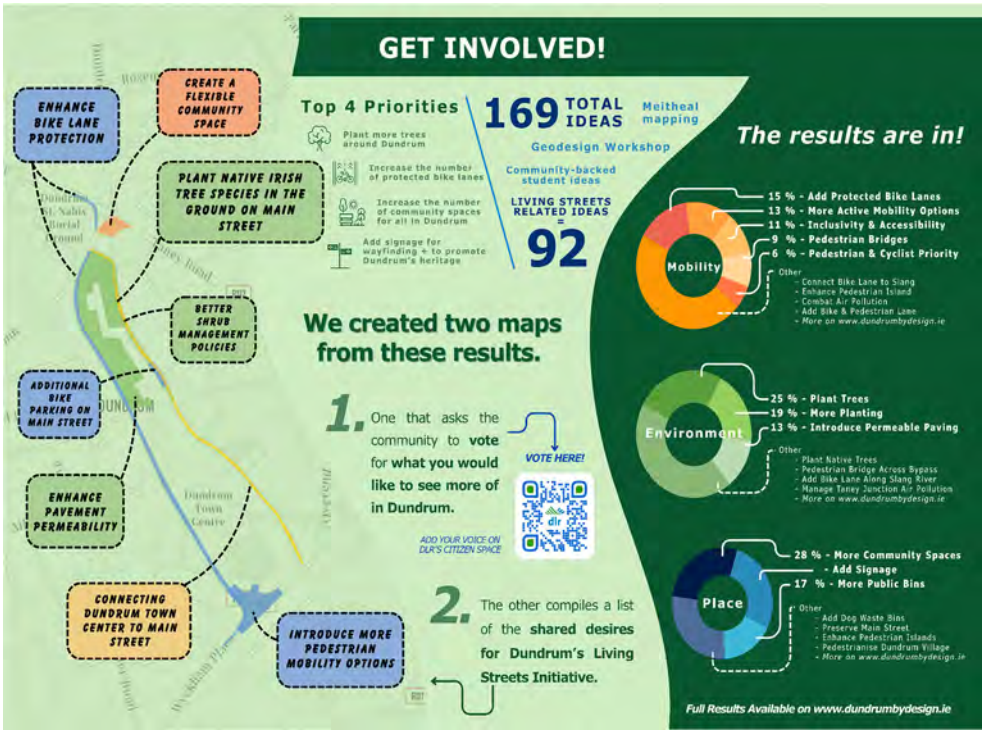

Fig. 2: Results poster used to communicate project progress to the Dundrum community

Analytics gathered as part of the initiative include a general sense of respondent demographics. Of the 149 mailing list registrations, 55% of registrants have identified as local residents, "I live in Dundrum", with a further 7% indicating that they work or live and work in Dundrum. These results align with the profile of respondents who have participated in the community voting, where 63% are a "local resident living in Dundrum" and 2% are a "local business owner/employee". Demographics also include a relatively even distribution between the proportion of men (43%) and women (40%) responding to the voting. Interestingly, a higher number of women (141) compared to men (136) responded as local residents on the community voting platform. Concurrently, the voting tool attracted increased participation

https://storymaps.arcgis.com/stories/54c6fddc4cdf4649875dd9802c8ca899#ref-n-p1imE7

from the 35–44 age group, which – alongside older age groups – had already shown active engagement in the initiative. These results underscore DbD's focus on engaging local voices, including those who work in Dundrum, in contributing to the initiative.

Qualitative results have been collected via the platforms employed. Original input collected on Meitheal created a set of common themes also evident across Minecraft, the community Geodesign workshop discussions, and the community voting responses. These pertained to urban greening (79% favoured votes), improvements to the active travel network (votes mixed across multiple ideas) and inclusive design (72% favoured votes). At the same time, data collection about the impact of DbD on participants advances as the initiative enters its final stages. Public response from the first geodesign workshop feedback survey presents a good perception, but is limited due to the low rate of responses. However, open-ended responses offer relevant insight towards participants' appreciation of the process and highlight areas for future improvement:

"Well done, good initiative." (Resident A)

"The technology gave small, fast moving results which were hard to see and follow. Great engagement from students. A real privilege to meet them." (Resident B)

"It was very interesting to participate in such a well-organised event." (Resident C)

In parallel, urban climate simulations, implemented in both GIS and 3D modelling environments (with a spatial resolution of 250m and 5m, respectively), include as primary outcomes the integrated assessment of i) heat stress and flood risk, ii) energy consumption and production from renewables, and iii) carbon balance accompanied by material flows and local storage capacity. These will be used in the second community workshop as essential components of the co-design process, to allow understanding and discussing the effects of changes in urban morphology and LULC (Land Use/Land Cover) on key environmental and comfort parameters. In addition, the synergies and trade-offs between climate action and socio-ecological co-benefits for local communities will be explored. The baseline scenario reflects the current climate and LULC, while alternative design scenarios under future (2030-2050) climate change incorporate the climate-resilient urban design solutions informed by the 92 ideas co-designed within Living Streets.

4 Discussion and Conclusion

DbD represents an innovative direction in representing citizen contributions to urban design processes in early urban design discourses. Improving accessibility and accounting for external circumstances, such as engagement fatigue or tech savviness, leads to greater trust, stronger connections and a climate-sensitive design. Applying a multi-faceted technological approach enables all stakeholders to collaborate within the context while responding to the Living Streets initiative. By simplifying the engagement process and leveraging the benefits of different platforms, the initiative provides multiple phases at which the community can provide input. Employing a pedagogical approach within the DbD partnership contributed to innovation and expanded visualisation possibilities, creating a space for knowledge exchange between students and the community. Key benefits to all three partners, UCD, DLR and the Dundrum community, include informed policy development grounded in realistic and tested simulations.

4.1 Assessing Digital Workflow Effectiveness in Geodesign

DbD demonstrates measurable workflow effectiveness across the four key dimensions developed by LEE et al. (2022). "Feasibility" is evidenced through successful multi-platform orchestration (Meitheal, GeodesignHub, Minecraft, Climate Modelling), engaging 160+ young people, generating 169 community ideas, and achieving 88,000+ social media views. 'Value' is reflected in organic engagement: mailing list growth to 149 registrations and 455 votes on contested ideas. DLR officials confirmed the initiative's value, stating it was *"useful to hear from the community as to what they would like to see in Dundrum"* and noting that *"the climate scenarios will be an input to future design that we would not otherwise have available to us"*. 'Change/Action' demonstrates tangible outputs through the transformation of scattered inputs into 92 structured Living Streets ideas and a number of alternative design scenarios, translating community visions into technical recommendations, though DLR noted it is *"too early to say"* which specific ideas will be incorporated into the final design. 'Sustainability' presents mixed prospects: positive indicators include the institutional partnership structure (UCD-DLR-community) within PROBONO, pedagogical integration with UCD Architecture curriculum, and the live Minecraft server maintaining youth engagement. However, community engagement relies on project-funded activities with no post-PROBONO participation mechanisms, risking participation fatigue without formal feedback loops reporting how inputs influenced final decisions.

DbD embodies the critical success factors identified by ATAMAN et al. (2025) and ATZMANSTORFER et al. (2025): transparent multi-channel dissemination; multi-scale data integration connecting local knowledge (geolocated Meitheal inputs across eight territorial systems) with expert analysis (climate modelling); active engagement between residents and designers facilitated through UCD student interventions; and context-specific focus on Dundrum's 2023 Local Area Plan priorities. DbD employs a hybrid approach, strategically combining digital platforms with high-visibility traditional engagement, including community meetings, workshops, and a student-curated tactical urbanism event. This multi-channel strategy mitigates tech-literacy barriers by ensuring residents encounter the project through both physical presence and digital platforms, aligning with TEKLER et al.'s (2024) emphasis on qualitative assessment.

While DbD demonstrates strong workflow effectiveness, assessing participation impact reveals that the process is still underway. VRYDAGH (2022) introduced the Sequential Impact Matrix (SIM) methodology tracking with six stages: (1) decision-makers' pre-participation preferences, (2) citizen inputs, (3) post-participation decisions, and (4) congruence analysis between ideas and outcomes. DLRCoCo provided documentation of pre-participation priorities (Stage 1) through the Dundrum Local Area Plan 2023, revealing existing priorities for traffic management, pedestrian safety, and public realm enhancement. DbD successfully documents stages 2 and 3, capturing 92 Living Streets ideas and establishing community voting, with documented community priorities showing strong alignment with DLR's medium-term vision for pedestrian priority, heritage preservation, and placemaking interventions. However, as DLR noted, it is too early to say at this stage in the design process which specific community inputs will be incorporated (Stage 4).

While congruence between DbD inputs and DLR's pre-existing priorities is evident, the timing of the assessment means concrete adoption decisions are not yet available to fully validate participation impact. DLR confirmed that *"there will be further community engagement in*

the preparation of the scheme", though specific mechanisms and timelines are still being determined. A complete participation impact assessment will require tracking which ideas are adopted and establishing formal mechanisms demonstrating how citizen inputs influenced final outcomes.

4.2 Limitations to Community Engagement

Early meetings with DLR uncovered the authority's positivity in adapting this approach, stemming from first-hand accounts of the power of community engagement in other Living Streets schemes. Officials, during the initial meeting in May 2025, indicated that councillors welcomed UCD to the team, with the former senior engineer describing it as *"perfect timing"*. DLR, understanding the sentiments of the general public in Dundrum, *"locals in Dundrum feel like they are being left behind"*, employed UCD's leading experience in spatial mapping because of their interest in *"methods and tools that help people talk, understand one another, and find cohesion. In particular, tools that support the public in better understanding the challenges and the interventions to be implemented. The question is not if these interventions will happen, but how, which is why collecting community input is so important."* Furthermore, the local authority would benefit from climate assessments and simulations based on the value added through this process.

While the results of DbD look promising, important factors might limit the deployment of the full potential of digital tools in encouraging citizen participation. Those without tech literacy are limited in the knowledge and capability to add inputs. Researchers aimed to mitigate this by employing traditional methods to supplement the digital approach, including public talks, flyer distribution, street engagement with a banner, one-to-one meetings with community members and drop-in sessions. The interpretive nature of Meitheal may also cause slightly inaccurate results when interpreted by researchers. Meanwhile, low participation numbers in the initial Knowledge-Gathering Phase (16 community members at the Geodesign workshop) ultimately may have promoted partially biased or inefficient ideas for community voting, with topics skewed towards issues raised only by minor yet active groups. Further research and methods can explore pairing technological and traditional approaches to create a holistic picture, boost early participation numbers and include extended deadlines where any type of community member can provide input when the project receives public credibility and trust.

In conclusion, leveraging multiple types of digital technologies provides possibilities for encouraging co-production of knowledge, co-design and co-creation. The DbD initiative highlights that a sound structure, interoperability and transparency can promote the snowballing of community inputs between various platforms and phases. This, in turn, ideally encourages citizen participation and provides a solid base for a just climate transition. Moreover, the DbD workflow offers other institutions and researchers a replicable yet adaptable model. By applying this multi-faceted technological approach to urban design, local authorities and communities are better equipped to imagine and shape the future possibilities of urban areas.

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Landscape Architecture Education, Pedagogy and Curriculum

An Empirical Study of Multi-Objective Problem-Based Learning in Landscape Architectural Design Education

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Abstract: As technology in analysis and simulation rapidly evolves, landscape architecture design and education must adapt to remain relevant. There is an increasing emphasis on multidisciplinary education approaches within certain fields, and this is also significant in landscape design practice. This study introduces a method for integrating digital techniques into landscape architecture education to support multidisciplinary collaboration. The group constellation in design studios are adjusted according to the various stages of the course, and this method has been tested in a collaborative design environment. The findings indicate that incorporating multidisciplinary digital techniques into landscape design education is both feasible and valuable. Data and digital analysis and simulation are basic components in the method, and on-site survey has indispensable effect to work together with data. The teaching effect of concrete experience and active experimentation is better than reflective observation and abstract conceptualization. Furthermore, the combination of individual design processes within a single discipline and collaborative efforts to achieve multidisciplinary outcomes yielded positive teaching results.

Keywords: Design education, multi-disciplinary, green space design, acoustic environment design, walking environment design

1 Introduction

Landscape architecture is an inherently complex discipline that integrates diverse elements – ecological, social, and aesthetic – to achieve multiple, often competing, objectives. Traditionally, landscape design education has relied on studio-based learning to navigate this complexity. As noted by DE HEI et al. (2019), effective design education requires a robust framework encompassing interaction, clear learning objectives, and structured guidance. While art focuses primarily on expression, design serves practical functions requiring coordination across various aspects to meet specific goals (TVERSKY et al. 2003). However, the rapid advancement of digital technology is fundamentally reshaping how these goals are defined and achieved, necessitating a significant evolution in educational approaches (FERRARI 2017).

In professional practice, digital technologies have driven a paradigm shift from qualitative representation to quantitative analysis and simulation (ZHOU et al. 2016). Initially limited to digital drafting (BEYL 1990), these tools now underpin computational design methodologies that enhance environmental analysis and intervention prediction. For instance, Geographical Information Systems (GIS) have evolved from basic impact assessment (PERRIS et al. 2001) to managing complex landscape element combinations (CAI et al. 2022) and analyzing user-centered social and perceptual aspects of the built environment (FERNÁNDEZ-ALVAREZ et al. 2022). Furthermore, simulation technologies now allow for precise optimization of specific design objectives, such as thermal performance (LI et al. 2023), lighting environments (LEE

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2013), wind patterns in traditional gardens (CHEN et al. 2024), and acoustic performance (BAR-SINAI et al. 2023). These advancements underscore a growing trend where multidisciplinary collaboration and data-driven decision-making are critical for addressing multi-objective challenges (MA & GALI-IZARD 2023, MUTHUMANICKAM et al. 2023).

Despite these transformations in practice, landscape architecture education often lags in fully integrating these multidisciplinary and computational approaches. Historically, education has prioritized drawing skills – starting with hand drawing to foster cognitive brain-hand coordination (EREN & YILMAZ 2022) and evolving into computer-aided design for visualization (NOVOA 2019, SENBEL et al. 2013). While visualization remains essential, the contemporary curriculum must expand beyond representation to include complex problem-solving, critical thinking, and cognitive flexibility (BROSENS et al. 2023, YÜKSEL & UYAROGLU 2021). Rajabzadeh et al. (2022) demonstrate that multidisciplinary education is vital for developing the collaboration skills necessary for modern practice. However, current pedagogical models often fall short in teaching students how to leverage digital tools not just for drawing, but for negotiating the trade-offs inherent in multi-objective design problems.

To address these pedagogical shortcomings, Problem-Based Learning (PBL) offers a critical theoretical framework. PBL is defined as a student-centered instructional strategy where learning is driven by complex, open-ended, and ill-structured problems rather than direct instruction (BARROWS 1986, RAJABZADEH et al. 2022). In the context of landscape architecture, PBL is particularly relevant because design challenges are inherently "wicked" – they lack a single correct solution and require the synthesis of conflicting ecological, social, and aesthetic goals. By situating learning within authentic problem scenarios, PBL compels students to actively engage in the decision-making process. It provides the necessary structure for students to apply digital technologies not merely as drafting tools, but as analytical instruments to solve the "multi-objective" complexities found in professional practice.

To bridge the gap between traditional pedagogical frameworks and contemporary technological needs, this study aims to develop a method that integrates digital technology into landscape design education. The objective is to enhance students' technological proficiency and negotiation skills to create comprehensive design solutions. By establishing a structured methodology for incorporating digital tools into the curriculum, this study seeks to impart essential digital skills while maintaining the core values of the traditional design studio. A course was implemented based on this methodology, and its outcomes were evaluated through the lens of Kolb's experiential learning framework (KOLB 1984). To achieve the study's objectives, three research questions (RQs) are addressed:

1) How can digital technology be effectively integrated into the design process, and what topics naturally lend themselves to this integration?

2) How can the diverse abilities required in landscape design be cultivated through a multidisciplinary teaching process?

3) How should grouping activities be structured to facilitate both the use of digital technologies and effective collaboration within design teams?

2 Methodology

This section outlines the structure of the method proposed in this study, as illustrated in Figure 1. To highlight the key features of this research, learning objectives, task characteristics, group constellation, guidance method and assessment method will be detailed in this section.

2.1 Learning Objectives

The objective of this method is to develop students' abilities to perform quantitative analysis and translate that analysis into effective design solutions. To achieve this goal, two key skill sets must be cultivated during the course. First, students should learn to identify major problems and devise appropriate solutions within specific domains. Given the complexity of contemporary landscape architecture, it is essential for students to handle knowledge from various fields to address site-specific challenges. This method allows students to select a related domain of interest to engage with. Second, enhancing social skills is crucial. Landscape architecture often involves collaborative work, where designers must navigate complex systems and address diverse issues. As multidisciplinary collaboration becomes increasingly important, the ability to adapt to these new dynamics within a traditional educational framework is a vital learning objective.

2.2 Task Characteristics

As illustrated in Figure 1, this method comprises three distinct phases: the survey report, planning structure, and final design. In the first phase, students conduct a survey report. They are provided with initial data about the site and tasked with identifying problems which will be the base of this problem-based study. If they encounter issues that require additional context, students are encouraged to seek supplementary information. This phase emphasizes the importance of formulating questions based on the official data provided. The second phase involves establishing the planning structure. Here, students learn essential techniques relevant to the problems identified in the first phase. They perform a single-disciplinary analysis to address these site-specific issues, which leads to the development of a preliminary planning structure. Solutions from different disciplines are presented independently and are directly overlapped. The third phase focuses on completing the final design. Students delve deeper into specific topics within their respective disciplines to create detailed design solutions that address the identified problems. In cases of conflicting issues among disciplines, students engage in negotiations to reach compromise solutions. Ultimately, these multidisciplinary design solutions are integrated into a final scheme.

2.3 Group Constellation

The group structure varies throughout the process, as illustrated in Figure 1. While the overall group size and duration are determined by instructors, students have the autonomy to select their group members. There are three distinct group configurations during the study. The first configuration involves large groups, which occur twice and include all students in the course. The first instance takes place during the initial phase, where collective efforts are made to create a comprehensive dataset, minimizing redundancy. The second instance occurs at the beginning of the second phase, where all students collaborate to learn various disciplinary techniques relevant to the design process. This exposure helps them make informed decisions

later on. The second configuration consists of small groups, which are utilized at all three checkpoints. Each small group has a designated leader and is responsible for producing a final design. This format is predominant throughout the process, as students primarily work in small teams to discuss, negotiate, and report their findings. Small groups facilitate collaborative learning, except in instances where students need to study specific topics together or delve into independent research. The third configuration is individual work, which takes place in the final phase. After selecting their specific problem and solution approach, students spend time deeply analyzing the ideal solutions, before exploring how their individual designs can integrate with others.

2.4 Guidance Method

In the course, teachers and group leaders will alternate to be the executer. Because students will proceed the design in class and out of class, teachers will guide the design in class and group leaders will be responsible for the work out of class. The role of teachers will be different corresponding to different kinds of group sizes. For large groups, teachers will act as coaches, which will impart basic information and skills. For small groups, teachers will be observant, which will try to find defects in the design. When it comes to individuals, teachers are experts, which will guide them how to execute detailed single disciplinary analysis.

2.5 Assessment

The primary assessment method employed in this study is group assessment, which promotes collaboration among students, because individual designs may compromise performance when addressing conflicts. Both formative and summative assessments play a crucial role in evaluating student progress. For formative assessment, scores from all three checkpoints contribute to the final grade. This is important because the collaborative nature of large group processes means that efforts are interdependent and influence subsequent work. As a summative assessment, the weight of the score in the final checkpoints will be dominant factor, because finding an optimal solution is essential in the problem-based learning.

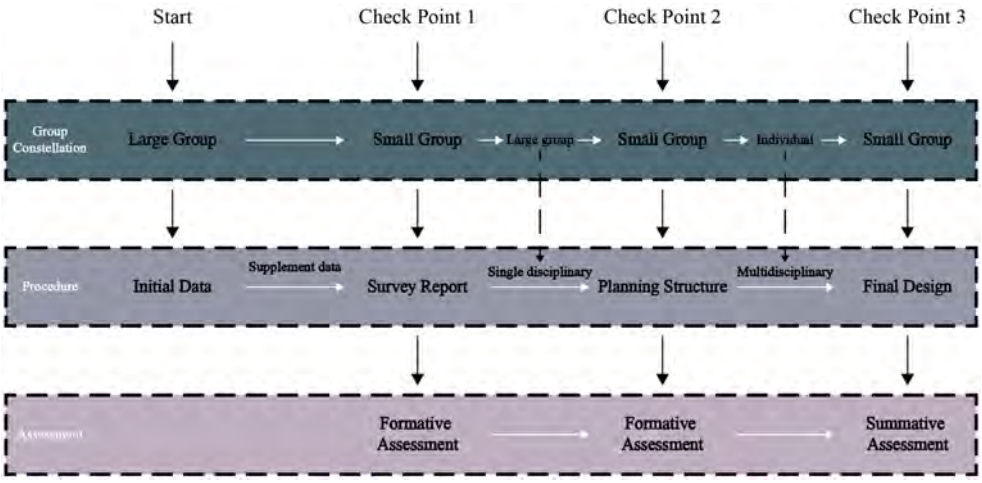

Fig. 1: Structure of the method

3 Case Study

This multidisciplinary teaching method was implemented during the spring semester of 2024. The landscape design program spans five years and consists of ten semesters, and this course focuses on the second semester of fourth-year students. The design site is located in Beijing, the capital of China. The course spans six weeks and includes three checkpoints, scheduled every two weeks. Sixteen students participate, equally divided into four small design groups. The scores from the first and second checkpoints each account for 20% of the total score, while the score from the third checkpoint constitutes 60%.

3.1 Multidisciplinary Skills Teaching

The multidisciplinary teaching approach in this course leverages the professional expertise of the teachers and covers three key areas: green space design, acoustic environment design, and walking environment design, in order to ensure the quality and depth of teaching. The method of analysis and simulation are comparted in the course. The green space section is on the first week, and the other two sections are on the third week. Green space design serves as the foundational element, as improvements in the sound and walking environments should build upon enhancements to green spaces. Preliminary research indicates existing issues in sound environment and walking environment, enhancing a comprehensive integration of design site and education strategies. Problems could be discovered in the classification and quantity of green spaces, and the types of green infrastructure present. The sound environment design component, illustrated in Figure 2, encompasses two main themes. The first theme focuses on noise map prediction, utilizing simulation techniques to forecast sound pressure level distributions before and after design interventions, thereby validating improvements. The second theme, soundscape design, aims to enhance emotional impact by thoughtfully integrating various sound components. The teaching of walking environment design skills is illustrated in Figure 2. Improvements in this area focus on simulating crowd movement under two scenarios: normal and emergency situations. Predicting normal conditions aids in designing a high-quality walking system that enhances daily life, while analyzing emergency scenarios helps optimize evacuation routes.

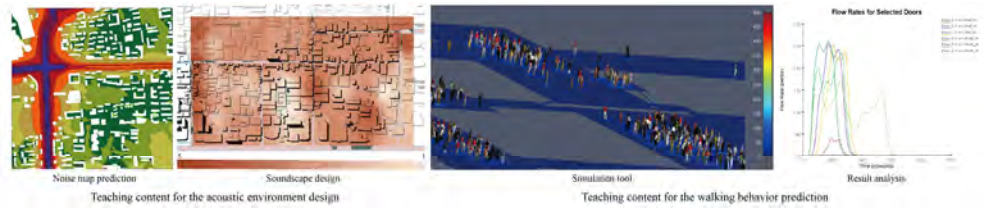

Fig. 2: Schematic diagram of the teaching content for acoustic environment design and walking behavior prediction

3.2 Outcomes in Checkpoints

The outcomes presented in Figure 3 indicate that the normalized difference vegetation index (NDVI) values are higher on the northeast, west, and southeast sides, reflecting better vegetation growth in these areas. In contrast, the NDVI value in the central area is lower. The

overall greening rate is 8.95%, which is significantly below the 30% standard required for urban area renovation. In terms of noise levels, the equivalent sound pressure level during the daytime in 2023 ranges from 45 to 65 decibels, with the primary concentration between 50 and 55 decibels. Notably, three key areas do not meet the standards for a healthy sound environment. The road network in Xicheng District is organized in a chessboard pattern, characterized by dense east-west roads and numerous scenic spots. However, parking resources are limited, highlighting the need for strategies to promote active transportation. The outcomes from the second checkpoint are illustrated in Figure 3. Each of the four groups established a foundational planning structure that aligns with their specific landscape design problems. Since the selected problems were determined by the students' preferences, not all groups addressed all three issues. Groups B and D tackled all three problems, while Group A concentrated on green spaces and pedestrian environments, and Group C focused on green spaces and acoustic environment. The outcomes at the third checkpoint are illustrated in Figure 4, which shows the final design of Group B as an example. This group incorporated all three themes into their project. Given that the number of students exceeds the number of themes, one student analyzed each topic to facilitate decision-making during any disputes. It can be noticed that the final design includes more details. Additionally, the planning structure at this stage differs slightly from the previous checkpoint due to interdisciplinary adjustments.

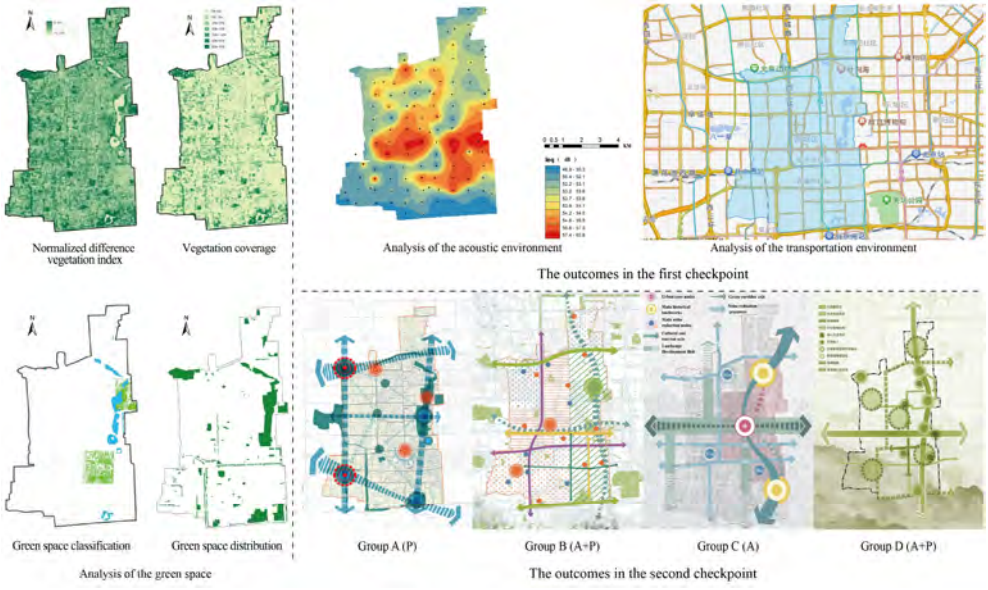

Fig. 3: The outcomes in the first and second checkpoint. The letter in the bracket indicates the theme that each group selected. 'A' means acoustic environment design, and 'P' means pedestrian environment design.

Fig. 4: The outcomes in the third checkpoint

3.3 Evaluation of the Learning

This study employs a questionnaire to evaluate the teaching process. The questions are designed based on Kolb's experiential learning theory and utilize a five-point Likert scale, ranging from "Strongly Disagree" (1) to "Strongly Agree" (5). In total, there are 19 questions. As illustrated in Figure 5, the first 16 questions address eight components of Kolb's learning cycle, which are categorized into four types of abilities: concrete experience, reflective observation, abstract conceptualization, and active experimentation. Each component includes two questions – one assessing the learning experience and the other comparing it to traditional methods. The final three questions aim to determine whether the group constellation provide adequate support for this interdisciplinary teaching approach. All students enrolled in the course participated in completing the questionnaire (N=16).

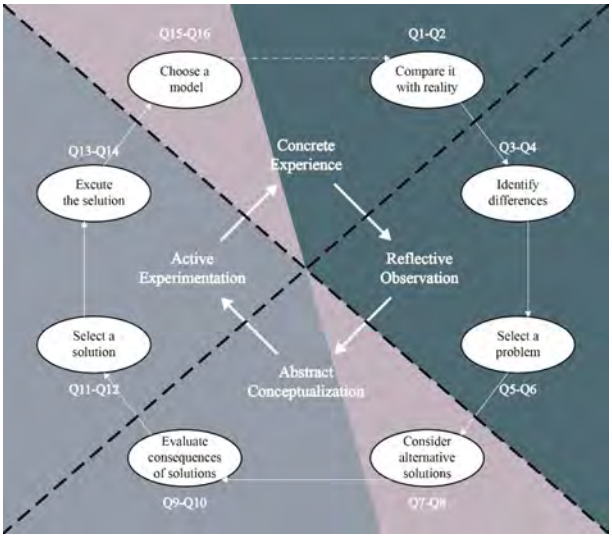

Fig. 5:
The correlation between evaluation method and Kolb's experiential learning cycle. The green part (Q1-Q6) focuses on the method of obtaining site information; the grey part (Q9-Q14) focuses on the method of analysis or simulation; and the pink part focuses on the combination of information and analysis.

4 Result

The survey results are presented in Table 1. All the questions received satisfactory ratings, with mean scores of at least 4.00, which indicates that the method used in this course is well-

received, with most students perceiving it as an appropriate approach for learning landscape design at their current stage.

Table 1: The descriptive statistics of explanatory and response variables in the evaluation (N=16)

Attribute	Satisfactory		Comparison		Range
	Mean	S.D.	Mean	S.D.	
Compare it with reality	4.56	0.51	3.25	1.18	1-5
Identify differences	4.19	0.54	3.56	1.03	1-5
Select a problem	4.19	0.54	3.31	1.01	1-5
Consider alternative solutions	4.25	0.45	4.31	0.60	1-5
Evaluate consequences of solutions	4.06	0.68	4.25	0.45	1-5
Select a solution	4.19	0.54	4.13	0.72	1-5
Execute the solution	4.50	0.52	4.00	0.63	1-5
Choose a model	4.44	0.51	4.00	0.37	1-5
Large group process	4.25	0.58	–	–	1-5
Small group process	4.00	0.73	–	–	1-5
Individual process	4.44	0.63	–	–	1-5

4.1 Evaluation of the Learning Experience

As shown in Figure 6, all eight components of Kolb's learning cycle received satisfactory ratings, with mean scores exceeding 4.00. Additionally, the course outperformed traditional methods, also scoring above 3.00 in comparative evaluations. These results indicate that the multidisciplinary approach employed in this problem-based landscape design course has been effective. This study employed two primary methods, utilizing three types of questions: information acquisition, analysis methods, and their combination. For information acquisition, we compared official data with traditional on-site surveys. While students generally expressed satisfaction with the information provided by official data, they did not fully endorse its superiority over on-site surveys. Notably, the standard deviation for this question was significantly larger, indicating that, despite the usefulness of official data, it cannot fully replace on-site surveys. Some students still rely on the insights gained from on-site observations to support their design work. In terms of analysis methods, we compared objective simulation and analysis with traditional design methods. Both the satisfaction level and comparison results exceeded 4.00, suggesting that objective simulation and analysis significantly enhance learning outcomes for fourth-year students. For their combination, the result is similar to the analysis method, which verifies the merits of the overall method in this course. Regarding the development of four key abilities, we observed that the satisfaction levels for reflective observation and abstract conceptualization were slightly lower than those for concrete experience and active experimentation. This discrepancy may be attributed to the relative ease with which students can engage with data analysis and simulation techniques compared to the more complex theories and research across disciplines, which are challenging to master within a six-week timeframe. While this approach effectively stimulates multidisciplinary collaboration, supplementary teaching may be necessary to address the gaps in more theoretical components.

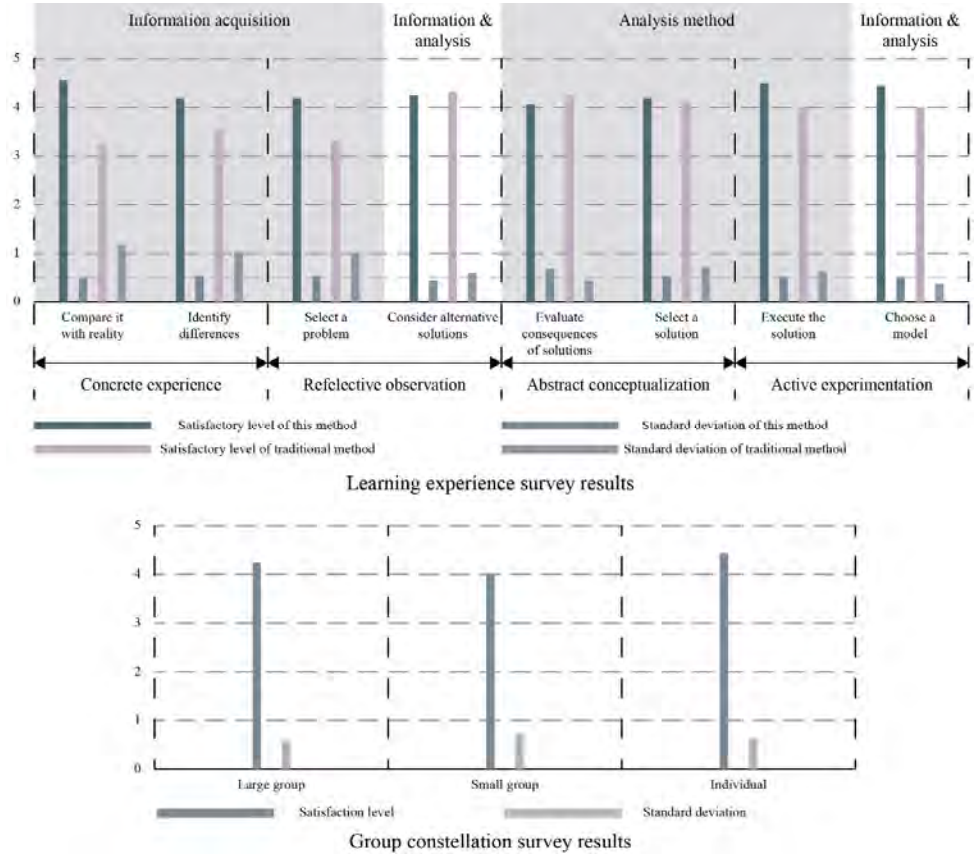

Fig. 6: The descriptive statistics of explanatory and response variables

4.2 Evaluation of the Group Constellation

The evaluation of group constellation is illustrated in Figure 6. Overall, students expressed a high level of satisfaction with the group arrangements in this course. Notably, the satisfaction with the individual learning process was the highest, indicating that students are comfortable with their disciplinary focus and are eager to engage in multidisciplinary collaboration. In contrast, satisfaction with the small group process was somewhat lower. This may be attributed to the fact that small groups were predetermined before students selected their specific disciplinary areas. If students opt for the same discipline, adjustments will be made within those small groups to facilitate effective collaboration.

5 Conclusion

This study demonstrates the potential for integrating multi-objective problem-based learning within traditional group-based landscape design studios. It highlights the multidisciplinary nature of landscape design and argues for an educational transformation to accommodate this

trend. Given the complexity of landscape architecture, employing a multidisciplinary approach to address multi-objective problems proves to be effective. The findings support the efficacy of this teaching method in fostering various abilities among students, as outlined in Kolb's experiential learning theory, based on their feedback. The study reveals that data can be more effectively analyzed when combined with objective analysis and simulation methods, which are increasingly popular in related fields. However, some students still require on-site surveys to gain a comprehensive understanding of their design sites. For most fourth-year students, incorporating objective analysis and simulation methods aids in analysis, evaluation, and decision-making. The multidisciplinary approach successfully cultivates all four abilities identified in Kolb's experiential learning theory. However, it is slightly less effective in promoting reflective observation and abstract conceptualization, with higher outcomes in concrete experience and active experimentation. Moreover, the varying group sizes within the group constellation effectively support multidisciplinary education. The successful integration of individual disciplinary design processes prior to collaboration enhances this educational approach.

Acknowledgments

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Generative AI as a Co-Designer: A Large Language Model-Driven Participatory Framework for Rural Cultural Landscapes

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Abstract: ***Background:*** Amid the dual contexts of rural revitalization and the widespread integration of artificial intelligence, participatory rural planning faces significant challenges, including multi-stakeholder negotiation and the preservation of cultural heritage. ***Objective:*** This study aims to visualize the goals of each stakeholder, identify and address their demands, and thereby enhance the cultural and innovative qualities of landscape projects, establishing an efficient model for rural revitalization. ***Method:*** We propose the PLDG model, which leverages large language models to simulate multi-character dialogues. Through multimodal semantic extraction and iterative consensus generation, the framework produces optimized landscape plans. ***Results:*** Using Ma Jia Di Village as a case study, the PLDG model significantly improved cultural compatibility by 145.4%, increased the villagers' participation index (PI) from 36 to 90, and enhanced the level of design innovation. ***Conclusion:*** This framework provides a novel paradigm and practical tools for human-machine collaborative rural planning, supporting more effective and culturally sensitive landscape design.

Keywords: Collaborative design, large language models, participatory design, rural cultural landscapes

1 Introduction

In rural revitalization, a key challenge lies in ensuring that rural areas keep pace with modern development while enabling stakeholders to meaningfully engage with and recognize revitalization efforts. The diverse roles and interests of stakeholders often give rise to conflicting priorities. Additionally, because the adjustment process is difficult to control, design interventions frequently reflect the subjective imagination of designers, resulting in insufficient exploration of local culture. To address these dual challenges, managing stakeholder conflicts and preserving cultural heritage, the integration of artificial intelligence into the design process has become increasingly important (ARMIN et al. 2025).

However, existing AI-assisted tools, such as VR participation models (KELLY 2018), primarily focus on form modification or multi-sensory feedback and lack the capacity to simulate complex social negotiations or perform in-depth analysis of cultural semantics. Although large language models (LLMs) can simulate role-based conversations (SUH et al. 2024), their application to landscape planning remains challenging, particularly in extracting stakeholder conflicts through prompt-based approaches. Using prompt engineering to summarize cultural identity elements for multi-party negotiation also presents significant obstacles. Moreover, addressing these negotiation challenges fundamentally requires improving user participation efficiency. Enhanced participation not only strengthens local cultural engagement but also provides a template for effective human-AI collaboration. Therefore, this study aims to develop an LLM-based framework that simulates multi-party negotiation in rural landscape planning while incorporating local cultural semantics.

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This study developed a prompt template to simulate requirements refinement in traditional design projects using LLMs for collaborative discussion. The specific contributions are as follows:

1) Proposed a novel paradigm for human-machine collaborative planning by integrating "role-think" simulation, thereby extending participatory design theory.
2) Developed the first AI-based collaborative design framework for rural landscapes (PLDG), incorporating multimodal semantic extraction, cultural constraint generation, and an evaluation system.
3) Validated the framework, demonstrating significant improvements in cultural compatibility, community identification, and design innovation, key contributions to digital village construction.

2 Method

2.1 Overview of the PLDG System

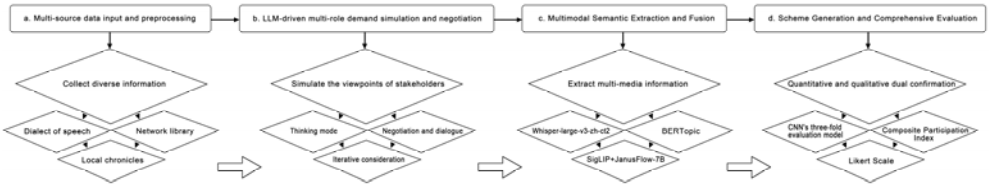

Fig. 1: The PLDG system workflow – the framework integrates four stages: multi-source data input, LLM-driven multi-role negotiation, multimodal semantic fusion, and scheme generation & evaluation, forming a closed-loop participatory design process

The PLDG (Multi-modal Participatory Landscape Demand Generation) model engages diverse stakeholders in cultural village landscape design to enhance project resilience and user satisfaction. It facilitates deliberation among participants, enabling them to articulate authentic requirements and negotiate mutual agreements. The specific operational process of the PLDG model is illustrated in Figure 1 and comprises the following steps: a. Multivariate Data Input and Preprocessing: Transcriptions from site interviews, local chronicles, policy documents, and other sources are integrated to form a comprehensive knowledge base for demand analysis. b. LLM-Driven Multi-Role Demand Simulation and Negotiation: Four key roles, villagers, tourists, designers, and investors, are assumed. Thought-pattern prompt words are incorporated to simulate dynamic conversations and negotiations among these roles. c. Multimodal Semantic Extraction and Fusion: During the simulation in step b, images, audio, and text generated through the conversations are extracted using fixed codes, enhancing both their visual and cultural semantic elements. d. Scheme Generation and Comprehensive Evaluation: Designers use Stable Diffusion to generate initial renderings from culturally enriched consensus texts. The evaluation compares this approach with traditional design methods from two perspective; Perceptual: semi-structured interviews assess user experience; Rational: blind reviews, CNNs, and a participation index (PI) measure cultural compatibility, innovation, and engagement. These interconnected steps map design proposals to user requirements, broadening innovation scope while ensuring culturally informed, participatory outcomes.

2.2 Multi-Character Simulation and Thought Chain Prompt Template

During the integration of the PLDG template into the early stages of landscape design projects, several challenges were encountered. Users often expressed their requirements vaguely and provided input in diverse formats. Additionally, reconciling conflicting demands among stakeholders proved difficult. Furthermore, cultural elements generated from prompts were frequently inadequately represented, limiting their effective incorporation into the design process.

Stakeholders' diverse backgrounds and perspectives lead to varied expressions of thoughts and demands in multi-user landscape projects (TANG & CHUNG 2024). This diversity is a primary reason why user requirements are often vague and presented in heterogeneous formats. Challenges in data collection can result in insufficient extraction of cultural elements, compromising design authenticity. Constraining AI reasoning logic can facilitate smoother dialogues, expand the expression of users' subconscious thoughts, and improve communication precision (ZHANG et al. 2023). In the PLDG system, steps a and b correspond primarily to the front-end dialogue phase. This phase involves two main processes: extracting requirements during step a, and negotiating conditions and intentions during step b. Depending on the conversation scenario, different AI reasoning perspectives are employed to engage effectively with users. This approach is designed to enhance the accuracy and depth of demand extraction during the LLM-based conversation stage.

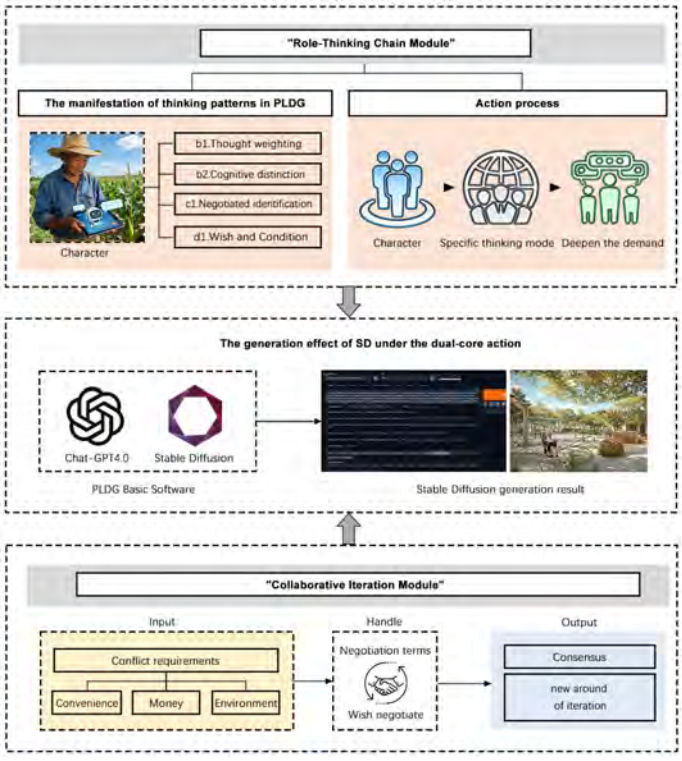

Fig. 2:
The intervention principle of the dual-core-driven PLDG system. This dual-core-driven principle includes: the input, processing and output processes of the role-thought chain module and the negotiation-iteration module. The "dialogue" in the picture is an AI-generated image: its function is to assist in explanation.

When traditional LLM outputs generate irresolvable conflicts, negotiation serves as the primary resolution mechanism (ZHU 2024). Accordingly, the PLDG model incorporates a negotiation process specifically designed to address identified demand conflicts. Research revealed that stakeholders often gain new insights and generate additional requirements when reviewing outputs alongside newly produced text. As these new demands emerge, the classification of factors into negotiable and non-negotiable categories may shift, prompting further rounds of negotiation. These iterations reflect incomplete demand exploration rather than changes in stakeholder preferences. Within the PLDG dialogue system (step b), prompt word templates are used to identify negotiable versus non-negotiable issues and to facilitate negotiation of intentions and conditions. Step c then implements an iterative intervention to ensure satisfaction with semantically integrated designs. If users express dissatisfaction, the system redirects them to step **b** to initiate another negotiation cycle. This iterative process effectively resolves conflicting interests, while multiple interactions of information enhance the resilience, coherence, and rationality of cultural expression.

By integrating role-thought chains and iterative negotiation into the template, generative AI progressively reveals reasoning pathways that leverage diverse modes of thinking, allowing humans to directly examine the entire cognitive process (Fig. 2). Negotiation effectively resolves conflicting demands, while the role-think framework addresses ambiguity in requirement expression. The iterative implementation establishes a solid technical foundation for cultural preservation. This integrated dialogue mechanism, combining thinking, negotiation, and iteration, subconsciously uncovers users' latent needs and significantly enhances the quality of landscape design projects.

2.3 Theoretical Basis of Evaluation Indicators

Rural revitalization primarily emphasizes cultural authenticity in landscape design. For example, Su et al. (SU & YANG 2025) employed expert scoring to assess landscape cultural levels. In the PLDG model, outputs, software-generated images, require expert evaluation of cultural content to validate their cultural appropriateness. While validating cultural fidelity is important, assessing whether outcomes align with subjective user needs, not solely cultural attributes, requires statistical analysis of process data, such as participation and innovation metrics. Trunfio et al. (TRUNFIO & ROSSI 2021) demonstrated that participation has a decisive relationship with behavior, time, and output. Similarly, the PI derived from the social media engagement measurement formula proposed by Forrester aligns with the AI dialogue model validation in the PLDG framework. However, surface-level data inadequately captures innovation, necessitating vectorization to quantify this abstract construct. This approach aligns with Daryanavard Chounchenani et al. (DARYANAVARD CHOUNCHENANI et al. 2025), who explored innovation in landscape design using CNN-assisted aesthetic evaluation.

2.4 PLDG Assessment Strategy

To evaluate the effectiveness of the PLDG model, we adopted a hybrid approach combining quantitative analysis with qualitative feedback. The evaluation focused on four key aspects: cultural compatibility, degree of innovation in the design plan, level of stakeholder participation, and users' perceptions and reflections derived from conversations facilitated by artificial intelligence.

Cultural Compatibility: To assess cultural compatibility, visual renderings of the landscape schemes were collected as baseline reference data. Fifty experts in cultural heritage were invited to evaluate and score five subcategories of cultural heritage (YANG 2020), including: Degree of restoration of regional symbols Adaptability of homestay activities Authenticity of local materials and craftsmanship Villagers' emotional identification with the design Ability to modernize and reinterpret cultural elements (VUJKO et al. 2024) A traditional control group was established by generating SD renderings from AI-generated prompt texts for comparative analysis. Given the broad scope of cultural compatibility, the evaluation was divided into these five elements to provide a quantitative basis. Responses were recorded using a 5-point Likert scale, enabling a robust comparative assessment of the PLDG model versus traditional design approaches.

Participation: To address the limitations of overly empirical research and strengthen evidential validity in assessing the PLDG model, our team collected original data generated during both the PLDG experiments and traditional conversation processes. This data was used to evaluate levels of user participation and cultural innovation. We employed the comprehensive PI formula proposed by Forrester (PALERMO & DELAINE 2023) to quantitatively assess user participation within the PLDG system. During the experiments, three key elements were recorded: the number of user behaviors, the span of user activity, and the output of results. These metrics were processed using the PI formula to generate a participation score ranging from 0 to 100, providing an objective measure of engagement within the PLDG framework.

Innovation – Degree of the Plan: To objectively assess the effectiveness of the PLDG model, vector data generated by the LLM throughout the experiment were analyzed. Using a CNN-based three-dimensional evaluation model, vector data from various stages of the design process were sorted and collected. Three key elements, visual innovation, semantic feasibility, and stylistic usefulness, were weighted and integrated through machine learning to calculate the overall degree of innovation for each plan, represented as the average input weight (GATYS et al. 2016). This metric was then compared with equivalent data derived from traditional AI dialogue generation methods, enabling a comprehensive comparative analysis of the PLDG model's performance.

3 Case Study

3.1 Site Selection

Ma Jiadi Village is located in the northeastern part of Yangling District, with the Xiaowei River flowing around it. The average summer temperature is 2-3℃ lower than that of nearby Xi'an. With nearly a thousand years of farming history, and situated near the Xiaoling Mountain Wetland and Fenghuangling Forest Belt, the village is often described as a "paradise hidden deep in the Xiaowei River." Supported by the "Agricultural Science City" policy, Ma Jiadi Village has established an agricultural history museum and a state-of-the-art smart agriculture experimental field. Concurrently, the village is undergoing national rural residential land reform under the "Three Rights Separation" initiative and is developing a model for rural revitalization. Substantial government funding, research teams, and social capital have also boosted tourism development. The village square is strategically located at the intersection of three key functions: daily life, tourism, and development. While preserving traditional ritualistic activities such as grain drying, weddings, funerals, and evening gatherings of vil-

lagers, the square must also accommodate tourists' practical needs, including parking, photography, and commercial outdoor displays. Additionally, it must meet developers' requirements regarding floor area ratio and commercial space efficiency. Ma Jiadi Village's rich agricultural and historical culture, combined with a mature policy-technology-capital environment and clearly defined spatial boundaries, make the village square an ideal site for testing the PLDG model's process of "cultural extraction – demand negotiation – benefit redistribution." The intensity of conflicts and the solutions proposed here reflect common challenges faced by tourism villages worldwide in balancing development with cultural preservation. For these reasons, Ma Jiadi Village was selected as the experimental base for the PLDG model.

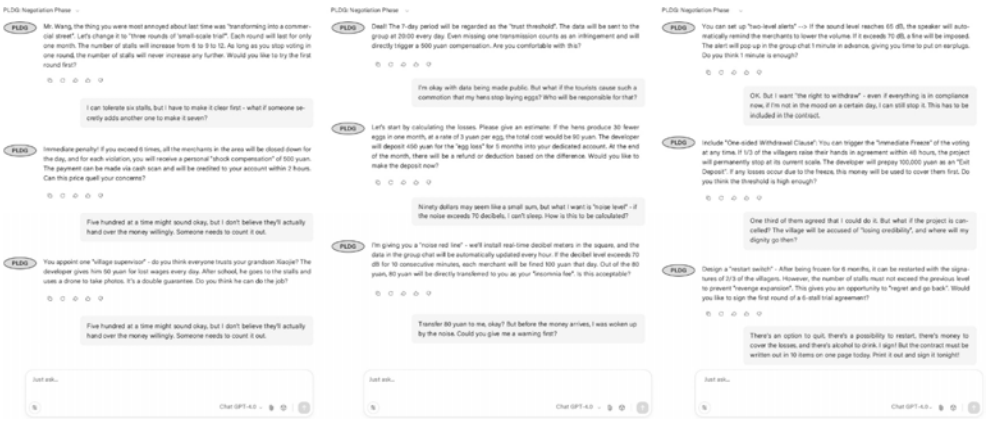

Fig. 3: The process of the d1 dialogue experiment in the PLDG model. Through nine rounds of dialogue between farmers and the PLDG model, the communication methods, negotiation procedures, and condition extraction processes were systematically demonstrated.

3.2 Experimental Procedure and Dialogue Examples

We employed the GPT-4 model to conduct a dialogue experiment within the PLDG framework, involving 12 villagers. The experiment followed the PLDG dialogue process: first, villagers' demands were collected (steps a1 and a2); next, different thinking modes were applied to deepen and clarify these demands (steps b1 and b2); finally, conflicts were resolved through negotiation of conditions and intentions (steps c1-d2), resulting in an iterative design solution. Figure 3 illustrates a key segment of the negotiation dialogue (step d1), in which the PLDG model employed negotiation and contract-based thinking to guide villagers in clearly defining negotiation conditions and intentions. Once a set of prompt words for a comprehensive landscape design that satisfied all stakeholders was generated, these prompts, along with an image of the village entrance square, were input into the SD system. SD subsequently generated 20 landscape design renderings (Fig. 4).

3.3 Sample and Method Validation

This study adopts a qualitative research paradigm, prioritizing depth over breadth. Purposive sampling was used to select 12 villagers for multi-round iterative dialogue experiments under

the PLDG model. The sample size was determined according to the principle of theoretical saturation. Empirical research by Guest et al. (2006) indicates that 12 participants from a homogeneous group are sufficient to achieve 88% theme coverage and 97% emergence of key themes. Waters et al. (NAVA & PERERA-BURGOS 2025) further validated that in-depth interviews with key informants, rather than broad sampling, better ensure data validity and robustness. All 12 participants were drawn from the same village, ensuring cultural homogeneity. The experimental design included multi-round dialogues (steps a1-d2) and control groups, generating rich data to achieve saturation and enable comparative analysis.

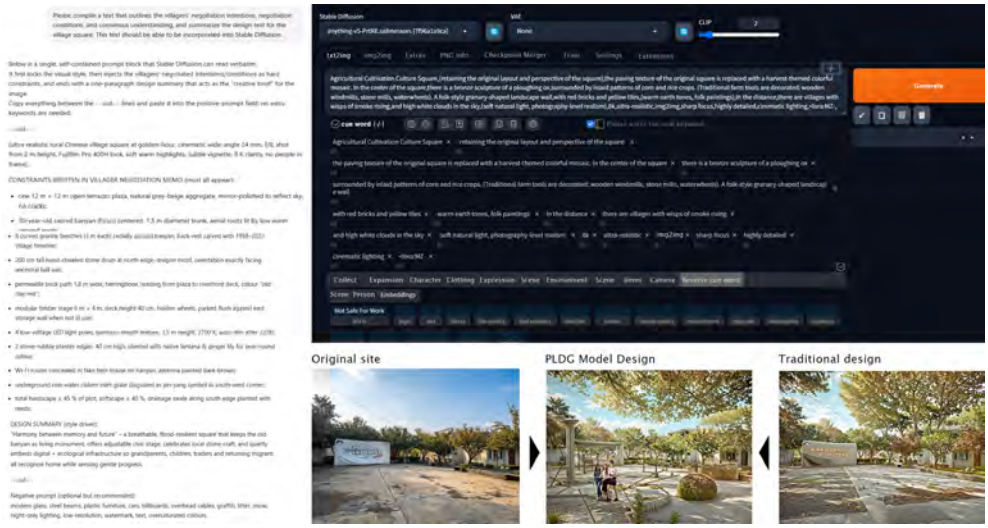

Fig. 4: Text generation workflow of PLDG model. This process includes: the final prompt text generated by PLDG model, the situation of SD text input, the comparison of the generation effects between traditional AI and PLDG system, all objectively reflect the effectiveness of the generation results produced by PLDG model.

4 Results and Discussion

4.1 Core Quantitative Results

The results indicated that all five elements of cultural compatibility under the PLDG model scored significantly higher than those generated by the traditional AI dialogue method. Average scores for each element ranged from 3.9 to 4.8, confirming that the PLDG dialogue system effectively captures and integrates cultural factors. Among these elements, the local authenticity of materials and craftsmanship received the highest score (4.8), representing the greatest difference compared to the traditional approach (1.6). Overall, the PLDG group outperformed the traditional AI group across all five elements and in total cultural compatibility. Statistical analysis revealed a Cliff's $\delta \geq 0.50$ and $p < 0.001$, indicating that the PLDG model demonstrates both statistically significant and practically meaningful improvements in cultural fit.

Participation and Innovation: In terms of stakeholder engagement, the PI for the PLDG model reached 90, markedly higher than the traditional PI of 36. The PLDG model demonstrated strong communication effectiveness, particularly among participants with lower educational and cognitive levels. An independent samples t-test comparing PI values from 12 villagers in the PLDG group and 12 in the traditional group showed that the PLDG participants scored significantly higher ($p < 0.004$), indicating that the PLDG negotiation process substantially enhanced overall participation, especially within the low-education cognitive subgroup. Regarding scheme innovation, weighted comprehensive evaluations were conducted using input widths $W \in \{128, 256$. The innovation value (Innov) for the PLDG group was 0.78, compared to 0.42 for the traditional AI dialogue group. A paired t-test confirmed that the PLDG group significantly outperformed the traditional group ($p < 0.004$), demonstrating that the PLDG model substantially increases the level of innovation in landscape design schemes. Overall, the PLDG model shows strong positive trends in cultural compatibility, stakeholder participation, and design innovation. However, the current experiment was limited to a single site and a small sample population, leaving the generalizability of the findings somewhat uncertain. Future research should expand the sample size and include multi-case comparisons to strengthen the robustness and applicability of the model.

Table 1: Comparison Table of Core Result Evaluation of PLDG and Traditional AI

Evaluation dimension	PLDG group (mean ± SD)	Traditional AI group (mean ± SD)	Improvement extent / Significance	Key Findings
Cultural Compatibility-The degree of restoration of regional symbols	3.9 ± 0.4	1.9 ± 0.5	Overall improvement of 145.4% ($p < 0.001$)	The score for the local nature of the material technology was the highest (4.8)
Cultural Compatibility-Adaptability of homestay activities	4.2 ± 0.5	2.3 ± 0.6		
Cultural Compatibility-Authenticity of local materials and craftsmanship	4.8 ± 0.3	1.6 ± 0.4		
Cultural Compatibility-Villagers' emotional identification with the design	4.0 ± 0.3	1.2 ± 0.3		
Cultural Compatibility-The ability to modernize and reinterpret cultural elements	4.4 ± 0.4	1.8 ± 0.4		
Villager Participation Index (PI)	90 ± 8.5	36 ± 7.2	$p<0.004$, $d=6.90$	Significantly enhance the participation of individuals with low educational attainment
Design Innovation Degree (Innov)	0.78 ± 0.03	0.42 ± 0.03	$p<0.004$, $d=2.18$	CNN – 3D Model Validation of Effectiveness

4.2 Qualitative Discovery

User Perception and Satisfaction: Design projects should prioritize client satisfaction over designer preferences. Accordingly, the experiment incorporated semi-structured interviews

with users (TEKIN 2022). These interviews were conducted anonymously online and framed from both "experience" and "understanding" perspectives to evaluate the subjective value of the PLDG model. The interviews revealed that the highest user satisfaction was associated with "making design culture visible," which allowed participants to clearly articulate their needs. Thematic coding of the interview data identified several core themes: Enhanced cognition: "The pattern can be disassembled in this way for me to choose." Sense of process control: "I can stop and change at any step, as if holding the remote control of the design in my hand." Trust and caution toward AI: "It understands the 'flavor' in my dialect, but I am also afraid it might act recklessly one day." These insights suggest that the PLDG model not only facilitates accurate demand expression but also increases user engagement and trust, while highlighting the need for transparency and oversight in AI-assisted design processes.

4.3 Comprehensive Discussion

Dialogue as Empowerment (Tripartite Consultation Mechanism): The PLDG model integrates "villagers' oral accounts – algorithmic recitation – expert responses" into a real-time, rotating triangular negotiation chain. Each "disagree" click and every addition of a "negotiation condition" translates implicit interests, such as clan authority, land income, and welfare priorities, into measurable, immediately comparable consensus texts. Consequently, planning authority shifts from a single centralized designer to a dynamic, multi-point system involving villagers, algorithms, and experts. Anonymous dialogue initially reduces interpersonal pressures, while a low-cost, iterative approach brings potential economic conflicts to light well in advance. Online discussions address immediate issues, and offline structures supplement these interactions by engaging silent elderly groups and emergent clan alliances. As the conversation progresses, participants' sense of control and responsibility increases. Through transparent, iterative digital processes, the village's political structure is effectively reproduced and stabilized, ensuring equitable participation and the incorporation of diverse local perspectives.

When villagers saw their oral histories transformed into readable, modifiable texts, the dynamic shifted from passive compliance ("machine speaks, residents nod") to active co-creation ("residents speak, machine listens"). The most demanding task, an "eye-catching contest" concerning visual appeal, marked a pivotal moment, evolving from the mere "representation of culture" to "self-production and self-direction of culture." This transformation of subjectivity extended beyond textual dialogue to the construction, operation, and self-organization of local festivals. It encouraged villagers to actively engage in spatial production and cultural renewal as collaborators, forming a sustainable empowerment loop that combines intergenerational heritage with self-sustenance. Ultimately, this process establishes a lightweight and replicable "algorithm-assisted thinking" governance model, offering a promising approach to rural revitalization in the digital age. The integration of participatory dialogue, AI mediation, and iterative negotiation not only preserves local power and culture but also provides valuable insights for both theoretical exploration and practical application in rural development.

4.4 Theoretical Implications and Practical Applications

This experimental study theoretically proposed and systematically elaborated, for the first time, a new paradigm of human-machine collaborative planning that integrates "role-thinking" simulation. The juxtaposition of AI agents and local actors overcomes the "technological

suspension" dilemma in digital rural construction, demonstrating that technology becomes an endogenous driving force for rural development only after localized adaptation. This provides a theoretical pathway for the transition from "external empowerment" to "endogenous development." The study constructs a "constrained generation-consensus iteration" mechanism, transforming landscape design from a model of "expert authority" to one of "distributed intelligent negotiation." It advances the concept of "design democratization" from a theoretical ideal to an operable, algorithmic architecture, redefining innovation as a "participatory innovation" paradigm rooted in heterogeneous dialogue. At the methodological level, the study developed an original AI-driven collaborative design framework for rural landscapes, the PLDG model, which integrates multimodal semantic extraction, cultural constraint generation, and an iterative consensus mechanism. This framework is complemented by a multi-dimensional evaluation system, representing a first in China. At the practical level, tests in a typical village demonstrated the PLDG model's effectiveness in enhancing cultural compatibility, fostering community identity, and increasing design innovation. These results provide novel, replicable, and scalable tools for implementing digital rural revitalization. However, certain limitations remain in the experimental study, including the use of a single case site and a relatively small sample size, which may affect the generalizability of the findings.

5 Limitations and Prospects

This study demonstrates AI's integration into rural contexts through a digital landscape generation mechanism that combines multimodal semantic extraction with role-based negotiation. The research shows that the PLDG model can address diverse landscape design needs across various rural environments, providing a novel framework for digital rural construction. It also enables culturally authentic and feasible design solutions unconstrained by human cognitive limitations, representing a methodological innovation. However, several limitations should be acknowledged. The study relied on a single case site, a small sample of 12 participants, a single-language corpus, and AI training data that may carry inherent biases, limiting the model's ability to fully simulate human complexity. These constraints reduce the external validity of the findings. Additionally, current stakeholder power mapping lacks sufficient depth, breadth, and diversity. Future research should focus on multi-village, large-sample, and longitudinal studies to validate and generalize the PLDG model. Key directions include exploring the universality of its multi-field approach, developing offline workshop adaptations, and examining ethical considerations and power dynamics in AI-mediated negotiations. Such efforts will advance the PLDG model and digital rural development toward a "rural-specific AI" paradigm, guiding communities toward sustainable prosperity.

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Rider-Oriented Street Suitability Evaluation and Improvement Strategies: A Case Study of a Central Urban Area in Nanjing

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Abstract: Food delivery riders are intensive users of urban streets, yet their spatial needs remain insufficiently addressed in evaluation and improvement practices. This study proposes a rider-oriented street suitability evaluation framework integrating safety, efficiency, adaptability, and environmental support. Using GPS trajectory data, street view interpretation, and field observations, the framework was applied to twelve street segments in a central urban area of Nanjing.

The results reveal systematic mismatches between rider activity and street suitability, particularly on commercially active streets. Indicator-level diagnostics identify curb side adaptability as a critical constraint shaping rider behavior. By combining suitability evaluation with exposure analysis, streets were classified into diagnostic types, with Zhujiang Road and Danfeng Street illustrating diagnosis-driven, low-intensity improvement strategies. The study demonstrates how rider-oriented evaluation can inform more context-sensitive street improvement decisions.

Keywords: Delivery riders, street suitability, digital street analysis, curb side adaptability, incremental street improvement

1 Introduction

The rapid expansion of on-demand food delivery services has profoundly reshaped urban mobility patterns and street space usage in high-density cities. Food delivery riders have emerged as one of the most active user groups of urban streets, engaging in high-frequency and time-sensitive trips that combine continuous movement with short-term curbside stopping. Unlike conventional commuters, riders operate under algorithmically mediated work systems in which delivery efficiency, time pressure, and route choices are jointly shaped by platform rules and the physical street environment.

Existing studies on food delivery riders have primarily focused on labour relations, platform governance, and occupational risks, highlighting issues such as algorithmic control, income precarity, and unsafe riding behaviours (CHEN 2020, HEILAND 2021, LIANG 2024). Parallel research in transport and urban studies has examined traffic safety risks and behavioural patterns using crash statistics, questionnaires, and simulation-based approaches (FAN et al., 2022; CHO et al. 2023, CAI et al. 2024). While these studies provide important insights into rider behaviour and risk exposure, they often treat the street environment as a background condition rather than an active determinant shaping delivery activities.

Meanwhile, street design and evaluation research has developed a range of frameworks to assess walkability, cycling safety, and overall street quality, such as the Healthy Streets Approach and street audit tools (SOUTHWORTH 2005, NACTO 2013, TRANSPORT FOR LONDON 2017). These frameworks are largely oriented toward pedestrians, cyclists, or general traffic participants, and rarely account for delivery-specific behaviours, including frequent curbside stopping, short-duration parking, and repeated route traversal under time constraints.

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This paper argues that the mismatch between riders' behavioural characteristics and existing street evaluation frameworks constitutes a critical blind spot in contemporary street planning. To address this gap, the study proposes a "delivery rider-oriented street suitability evaluation framework" that explicitly incorporates riders' spatial behaviours, perceived needs, and street-level environmental features. Drawing on questionnaire surveys, semi-structured interviews, and GPS trajectory data collected from food delivery riders in a central urban area of Nanjing, the study constructs a multi-dimensional indicator system reflecting safety, efficiency, and spatial adaptability from a rider-oriented perspective.

Rather than pursuing statistical generalization, this study adopts a framework-oriented approach. Its contribution lies in demonstrating how fine-grained behavioral data and street-level spatial indicators can be integrated into an operational evaluation model. By linking suitability assessment with diagnostic interpretation, the framework provides a practical pathway from empirical evidence to targeted street improvement.

This study contributes to Digital Landscape Architecture by linking digital spatial analytics (GPS trajectories and street-view interpretation) with street-environment evaluation and diagnosis-driven improvement design. It demonstrates how data-informed methods can support evidence-based transformation of urban public space, a core concern of landscape architecture and street-scale public realm design.

2 Literature Review

2.1 Delivery Rider Research: A Multidisciplinary Landscape and The Missing Street-Design Link

Delivery rider research spans multiple disciplines and can be broadly categorized into three complementary areas of literature, each with direct implications for street renewal.

Platform labor and algorithmic management. Social science and labor studies show how platform governance, algorithmic allocation, and customer evaluation create time pressure and shape riders' spatial behavior, including risk-taking and rule negotiation in public space (CHEN 2020, HEILAND 2021, RODRÍGUEZ & ALLEN-PERKINS 2023). These insights clarify why riders may accept unsafe maneuvers or informal stopping practices, but they rarely specify how street design and curb regulation can reduce such structural pressures.

Operations research and delivery optimization. Logistics research models routing and dispatch under uncertainty and rider heterogeneity (QIAN et al. 2025). This line helps explain efficiency constraints and bottlenecks, yet typically treats the street environment as a background network rather than a designable system with curbside and entrance constraints.

Traffic safety and occupational health. Transportation safety and public health studies use naturalistic riding data and risk models to identify hazardous behaviors and exposure, such as risky turning or signal compliance under rush conditions (CHO et al. 2023, CAI et al. 2024, BONIARDI et al. 2024). While they highlight risk mechanisms, translating those mechanisms into street-segment interventions (e. g., intersection geometry, protected space continuity, curbside staging) remains limited.

Across these streams, a shared gap is evident: the literature seldom provides a coherent "needs-indicators-diagnosis-design" translation pipeline that planners can apply at the street-

segment scale. This motivates rider-oriented suitability evaluation as a bridge between rider studies and street renewal practice.

2.2 Multi-User Street Renewal and Curbside Governance

Street renewal has increasingly shifted from vehicle-oriented throughput to integrated goals of health, equity, and multimodal coordination. Practice frameworks emphasize prioritizing walking, cycling, and public transport, and improving comfort and perceived safety to support a healthy city (TRANSPORT FOR LONDON 2017, NACTO 2013). Within this shift, the curbside adaptability has emerged as a contested and scarce resource for short stops, loading/unloading, and arrivals, making curbside governance a key component of contemporary street management. Policy and practitioner work highlights that curb functions must be allocated through a combined package of rules, design, and operational management to balance efficiency and order (INTERNATIONAL TRANSPORT FORUM 2018, MITMAN et al. 2018). However, these frameworks primarily address general mobility users and institutional actors, leaving delivery riders – who combine roles as workers, riders, and curbside users – largely implicit in renewal agendas.

2.3 Street Evaluation Methods: From Walkability Audits to Multi-Source Computable Indicators

Street evaluation research has traditionally relied on audit tools and scales rooted in walkability, perceived safety, and environmental quality (CUNNINGHAM et al. 2005). With advances in multi-source urban data, studies increasingly quantify streetscape features from street-view imagery and GIS–for example, estimating street greenery as an environmental comfort factor (LONG & LIU 2017) and measuring age-friendliness through multi-source big data (WEI et al. 2024). In parallel, mobility analytics provides methodological foundations to couple movement behaviors with street networks through map matching and trajectory mining (NEWSON & KRUMM 2009, ZHENG et al. 2014, DU et al. 2025).

However, rider-oriented evaluation requires additional emphasis on curbside micro-stopping, entrance interface efficiency, and two-wheeler continuity/safety, which are not central in walkability-only instruments. Building on curb governance concepts (INTERNATIONAL TRANSPORT FORUM 2018, MITMAN et al. 2018) and multi-source measurement methods, this study develops a rider-oriented suitability indicator system that is designed to be transparent, computable, and directly translatable into renewal actions.

3 Methods and Materials

3.1 Research Framework and Analytical Logic

This study adopts a framework-oriented methodological approach to evaluate street space suitability from the perspective of food delivery riders. Rather than aiming for statistical representativeness of the entire rider population, the research focuses on developing a transparent, computable, and design-oriented evaluation framework. The framework explicitly links rider behaviour, street environment characteristics, and renewal strategies at the street-segment scale.

The analytical logic follows a sequential, five-step process:

1) Identification of delivery riders' work-related spatial needs through questionnaires and semi-structured interviews;
2) Translation of these needs into measurable street-level indicators;
3) Computation and aggregation of indicators to evaluate rider-oriented street suitability;
4) Identification of rider activity hotspots using GPS trajectory data to pinpoint priority improvement locations;
5) Formulation of targeted street improvement strategies by integrating suitability evaluation results with hotspot analysis.

This "needs-indicators-evaluation-hotspots-strategies" pipeline bridges multidisciplinary research on delivery riders with street improvement practice, providing an operational pathway from behavioural evidence to planning intervention.

3.2 Study Area

3.2.1 Spatial Scope

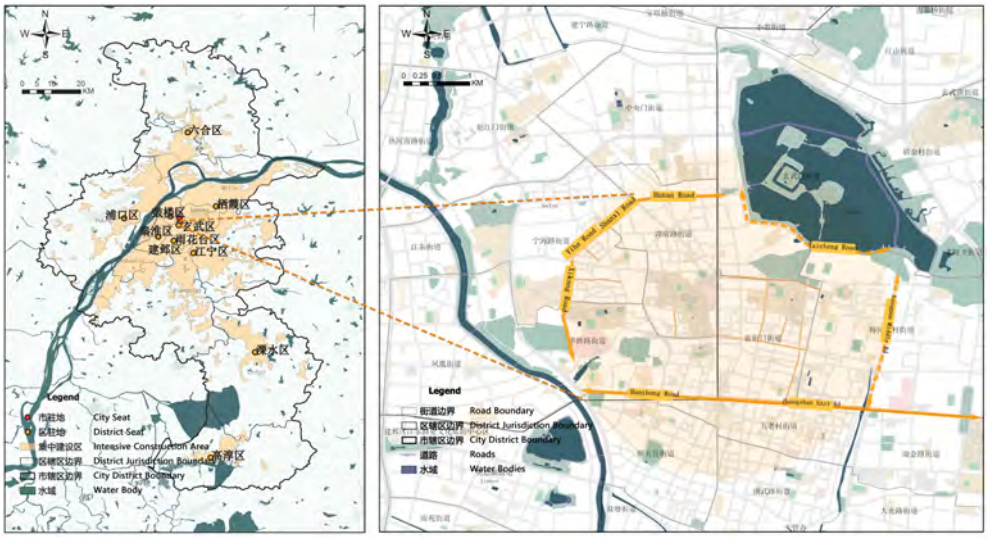

Fig. 1: Study Area (left: Nanjing City; right: specific spatial scope)

The empirical data were collected from the Xinjiekou-Sipailou area in central Nanjing. This area is a high-density, mixed-use urban district characterized by intensive commercial activities, a complex street network, and a high concentration of food delivery demand. It represents a typical context where delivery riders frequently interact with pedestrians, non-motorized traffic, motor vehicles, and curbside spaces.

Given that delivery activities are not constrained by administrative boundaries, this study defines the extended activity area based on the spatial distribution of riders' GPS trajectory points, pickup and drop-off locations, and stopping events. Kernel density analysis was employed to extract the contour encompassing 90% of riders' primary activity. Based on preliminary operational data, the extended activity area generally covers the central urban corridor extending east to Longpan Middle Road, south to East Zhongshan Road, north to the vicinity of Xuanwu Lake, and west to the Hunan Road-Shanxi Road-Xikang Road-Huju North Road corridor (see Figure 1).

3.2.2 Research Subjects

1) Rider sample selection

Rider samples were selected according to the following criteria: (i) a minimum work experience of two months to ensure a stable cognitive understanding of the study area; (ii) more than 90% of delivery trajectories and stopping activities occurring within the defined study area, covering commercial, residential, and campus-related delivery scenarios; and (iii) structural coverage of both platform-employed riders (with stable dispatching and fixed service areas) and crowdsourced riders (with flexible order acceptance and broader activity ranges).

A total of 103 riders were initially approached, and 95 completed the questionnaire, resulting in a response rate of 92%. Participation was facilitated through on-site recruitment, clear communication of data anonymity, and coordination with local delivery station managers to support device installation and follow-up.

2) Street samples

Based on functional characteristics and preliminary analysis of rider activity patterns, 12 representative street segments were selected as evaluation units. Each segment is defined as a continuous section between two adjacent intersections. The selected segments include commercial streets (Zhongshan East Road, Hunan Road, Zhujiang Road, Danfeng Street), residential streets (Beijing East Road, Yihe Road, Langya Road, Tianmu Road), and university-adjacent streets (Jinxianghe Road, Chengxian Street, Qingdao Road, Zhen Lane).

3.3 Data Sources and Collection

3.3.1 Spatial Scope

Table 1: Schematic diagram of naturalistic riding data of food delivery riders

	Timestamp	Longitude	Latitude	Speed ($m \cdot s^{-1}$)	Direction
1	2025-10-06 17:03:01	32.068655	118.811916	25	50° east of north
2	2025-10-06 17:03:06	32.06889	118.812215	21	34° east of north
3	2025-10-06 17:03:20	32.069781	118.813206	23	39° east of north
4	2025-10-06 17:03:31	32.070313	118.813861	37	44° east of north
	..	..	..	..	..

For riders participating in trajectory collection, a GPS device was installed on their electric bicycles. While in motion, the device recorded timestamps, latitude and longitude, and travel speed at a frequency of 1 Hz. More than 550,000 trajectory points were collected. These data were primarily used to compute objective indicators (e. g., travel speed and detour patterns), identify activity hotspots, and verify behavioural consistency.

Questionnaire surveys were conducted using a combination of online and offline methods to collect riders' socio-demographic attributes, subjective perceptions (e. g., perceived safety and comfort), and behavioural preferences. The reliability of the questionnaire data was confirmed with a Cronbach's α coefficient of 0.85. Semi-structured interviews explored behavioural motivations, latent spatial needs (e. g., charging and shelter), and perceived conflicts. Approximately 45 hours of interview recordings were transcribed and coded for qualitative analysis.

3.3.2 Street Spatial Data

Street spatial data were obtained through a combination of field surveys and street view verification. Field measurements included effective non-motorized lane width, curb length, intersection conflict points, and nighttime illumination levels, collected using laser rangefinders and illuminance meters. Tencent Street View API was used to supplement and verify street facility information. In addition, road network data, POI data, and traffic flow data were integrated to support indicator calculation and spatial analysis.

3.4 Data Processing

3.4.1 GPS Trajectory Data Processing

Trajectory data processing involved four steps. First, data cleaning was performed to remove abnormal points (speed >50km/h or <0km/h) and drift points with deviations greater than 50 m from the road network. Second, a Hidden Markov Model (HMM) was applied to map-match trajectory points to street segment IDs. Third, stopping events were identified using a speed threshold of ≤3 km/h and a duration threshold of ≥30 seconds, and further classified as business-related or rest-related stops based on POI association. Finally, kernel density analysis was conducted in Esri ArcGIS Pro 3.4 to generate maps of stopping hotspots and movement corridors.

3.4.2 Questionnaire and Interview Data Processing

Questionnaire data were processed using SPSS 26.0, with subjective scores normalized to a 0-1 range. Interview transcripts were coded using NVivo 12 to extract key categories such as behavioural motivations, latent needs, and perceived spatial conflicts.

3.4.3 Street Spatial Data Processing

Field survey and street view data were linked to street segment IDs to construct a street spatial attribute database comprising 16 indicators. ArcGIS was used to integrate street attributes with behavioural heat maps and stopping hotspots for subsequent evaluation.

3.5 Evaluation Indicator and Weight Determination

Table 2: Rider-oriented street suitability indicator system

Criterion layer (Weight)	Indicator	Meaning	Measurement Method
Cycling Safety (0.30)	Effective cycling path width	Usable width of non-motorized lane for riders	Field survey, average value (m)
	Separation from motor traffic	Degree of physical separation between motorized and non-motorized traffic	Field survey scoring (1–3)
	Intersection conflict density	Number of conflict points per intersection	Field observation (count)
	Pavement flatness	Proportion of pavement without potholes or cracks	Street view recognition + field verification (%)
Riding Efficiency (0.28)	Route detour rate	Ratio of actual riding distance to shortest path	GPS trajectory analysis
	Road network connectivity	Continuity of street segment in cycling network	Space syntax integration
	Intersection turning convenience	Ease of turning movements at intersections	Field measurement (m)
Curbside Adaptability (0.28)	Adaptable curb length	Proportion of curb suitable for temporary delivery stopping	GIS statistics (units/km)
	Density of temporary stopping spots	Number of delivery stopping opportunities per km	Space syntax accessibility index
	Distance to pickup/ delivery entrance	Average distance from curb to delivery entrance	GIS calculation (m)
	Parking buffer space	Buffer distance between stopping area and traffic flow	Field survey (m)
Environmental Support (0.14)	Nighttime lighting uniformity	Coverage and consistency of street lighting	Field survey scoring (1–5)
	Weather shelter provision	Coverage of rain/sun shelter facilities	GIS statistics (%)
	Rest facility density	Number of rider rest facilities per km	GIS statistics (units/km)

The indicator system consists of four criterion layers: Cycling Safety, Riding Efficiency, Curbside Adaptability, and Environmental Support. These criteria reflect key dimensions repeatedly emphasized in rider questionnaires, interviews, and prior literature. In total, 14 indicators were defined under the four criteria.

Indicators were quantified using either objective spatial measurements or subjective evaluation scores. To ensure comparability across indicators with different units and value ranges,

all indicator values were normalized to a [0,1] interval using min-max normalization. Indicators within each criterion layer were aggregated using equal weighting, reflecting the exploratory nature of the framework and the current lack of empirical evidence to support differentiated weighting schemes.

By aggregating criterion-level scores, a composite rider-oriented street suitability score was generated for each street segment. This score enables horizontal comparison across different streets and supports the identification of segments with relatively weak or strong performance from the delivery rider perspective.

Criterion weights were set as follows: Cycling Safety (0.30), Riding Efficiency (0.28), Curbside Adaptability (0.28), and Environmental Support (0.14). Higher weights were assigned to safety, efficiency, and adaptability, as these dimensions directly affect delivery feasibility and risk exposure during high-frequency riding and stopping. Criterion weights were assigned based on the relative importance consistently expressed in rider questionnaires and interviews, while indicators within each criterion were equally weighted to ensure transparency.

4 Results

4.1 Overall Street Suitability Scores

Based on the proposed evaluation framework, rider-oriented street suitability scores were calculated for the 12 selected street segments. All indicators were normalized to a [0,1] range and aggregated at the criterion level, resulting in comparable scores across street segments.

Table 3 presents the overall suitability scores as well as criterion-level performance for each street segment. The results reveal clear inter-street differences, particularly between commercial streets with intensive delivery demand and residential or university-adjacent streets with more stable spatial conditions.

Overall, commercial streets tend to exhibit lower adaptability and safety performance, whereas residential and university-adjacent streets show more balanced profiles despite generally lower delivery exposure.

Table 3: Rider-oriented street suitability scores by street segment

Street segment	Safety	Efficiency	Adaptability	Environmental Support	Overall score
Zhongshan East Rd	0.29	0.40	0.35	0.60	0.41
Hunan Rd	0.33	0.45	0.68	0.65	0.54
Zhujiang Rd	0.29	0.49	0.71	0.67	0.52
Danfeng Street	0.55	0.22	0.35	0.40	0.40
Beijing East Rd	0.65	0.70	0.50	0.70	0.63

Yihe Rd	0.80	0.55	0.45	0.55	0.61
Langya Rd	0.78	0.60	0.50	0.58	0.63
Tianmu Rd	0.75	0.65	0.55	0.60	0.64
Jinxianghe Rd	0.82	0.75	0.65	0.72	0.74
Chengxian St	0.72	0.68	0.65	0.72	0.68
Qingdao Rd	0.52	0.65	0.78	0.65	0.64
Zhen Ln	0.62	0.35	0.45	0.46	0.58

4.2 Criterion-Level Performance Patterns

At the criterion level, safety, efficiency, and adaptability exhibit distinct spatial patterns.

Safety performance is generally higher on residential and university-adjacent streets, benefiting from lower traffic speeds, clearer modal separation, and more legible spatial organization. In contrast, major commercial streets tend to score lower due to frequent curbside conflicts, informal stopping behavior, and limited physical separation between riders and motorized traffic.

Efficiency is primarily influenced by route continuity and entrance accessibility. Streets characterized by fragmented internal networks or frequent detours show reduced efficiency even when overall safety conditions are acceptable.

Adaptability displays the greatest variation among the three criteria. Streets with flexible curb conditions, surplus sidewalk width, or informal buffer spaces demonstrate higher adaptability, whereas spatially rigid streets with continuous barriers or strict curb regulations exhibit limited capacity to accommodate delivery-related stopping behavior.

4.3 Indicator-Level Diagnostic Profiles of Representative Street Types

To reveal the internal structure behind criterion-level scores, indicator-level diagnostic profiles were generated for representative street types (Figure 2).

Zhongshan East Road represents a Type I street characterized by high exposure and low suitability. Its profile is dominated by deficits in cycling safety and curbside adaptability, indicating a pronounced mismatch between delivery demand and spatial capacity.

Danfeng Street illustrates a Type III condition, where overall suitability is constrained primarily by limited curbside flexibility and entrance-related inefficiencies rather than extreme safety risks. Despite moderate exposure levels, rider activity remains concentrated due to its mixed-use surroundings.

Jinxianghe Road serves as a Type IV reference profile, exhibiting balanced performance across all criteria. Rather than representing an idealized street, it reflects a practically attainable configuration under existing urban conditions.

These profiles demonstrate that similar overall scores may conceal distinct internal limitations, highlighting the value of indicator-level diagnostics for targeted improvement.

Fig. 2: Criterion- and indicator-level diagnostic profiles of representative street types

4.4 Diagnosis-Based Street Typology

By integrating rider-oriented suitability and exposure levels, street segments were classified into four diagnostic types with distinct planning implications (Table 4).

This typology translates evaluation results into a decision-oriented framework.

Notably, Zhujiang Road and Danfeng Street exhibit moderate suitability combined with sustained rider exposure. Although neither represents an extreme mismatch case, both highlight contexts where improvement potential is high due to identifiable and localized performance deficits, particularly in adaptability and efficiency.

Table 4: Diagnosis-based street typology combining suitability and exposure

Type	Suitability level	Exposure level	Planning implication
Type I	Low	High	Urgent intervention priority
Type II	High	High	Performance reinforcement under high demand
Type III	Low	Low	Selective improvement / bottleneck correction
Type IV	High	Low	Reference / benchmark

5 Discussion

5.1 From Diagnostic Results to Intervention Priority

Rider activity was mapped using GPS trajectory data to contextualize suitability evaluation and identify spatial priorities for improvement (Figure 3). The resulting heatmap reveals a highly uneven spatial distribution of rider movements, with pronounced concentrations along major commercial corridors as well as at interfaces between commercial, residential, and institutional land uses.

Fig. 3: Rider speed and stopping profile (left) and GPS-based trajectory heatmap (right)

Zhongshan East Road exhibits the most critical overlap between high exposure and low rider-oriented suitability and therefore functions as a diagnostic benchmark. However, its large spatial scale, heavy traffic volume, and strong regulatory constraints limit its value for illustrating transferable street-level improvement strategies.

In contrast, Zhujiang Road and Danfeng Street are embedded within mixed-use urban contexts characterized by overlapping delivery demands from students, residents, and nearby commercial establishments. Despite relatively high rider exposure, their suitability deficits are primarily structural and localized, particularly in curbside adaptability and riding efficiency. This combination of high real-world delivery demand and improvable spatial conditions makes them suitable cases for illustrating feasible improvement strategies.

5.2 Case-Based Street Improvement Illustration: Danfeng Street

Danfeng Street is used to illustrate how rider-oriented suitability evaluation informs targeted improvement strategies.. Both streets experience intensive short-distance delivery activity and frequent curbside stopping, yet lack sufficient flexible space to accommodate these behaviors safely and efficiently.

Rather than comprehensive redesign, proposed strategies focus on targeted, low-intensity spatial adjustments at the curbside and entrance interface. These include the reorganization of curbside adaptability functions, the introduction of flexible or time-based stopping zones, and minor access optimizations aimed at reducing detours and informal stopping behavior.

These cases illustrate how diagnosis-driven improvements can translate quantitative evaluation results into implementable and transferable strategies for dense, mixed-use urban environments.

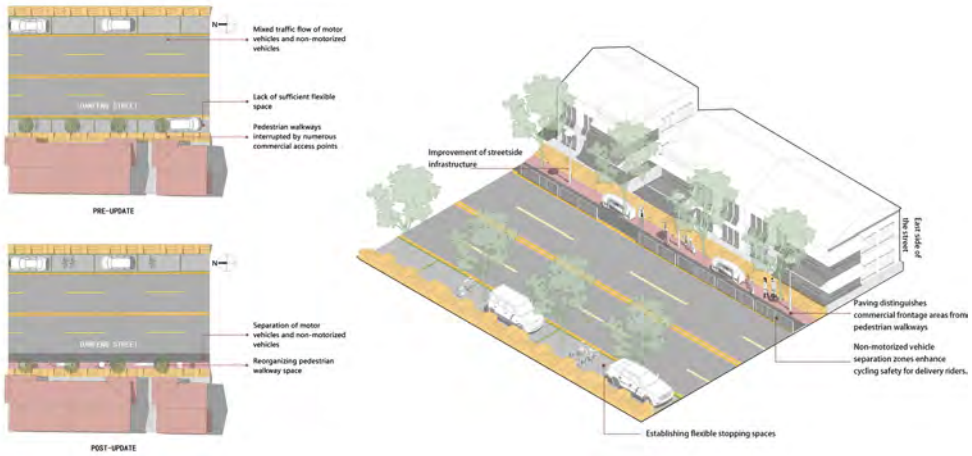

Fig. 4: Danfeng Street Renovation Diagram (Plan View on the Left, Axonometric View on the Right)

6 Conclusion

This study developed a rider-oriented street suitability evaluation framework that integrates criterion-level assessment with indicator-level diagnostics to better capture the spatial re-

quirements of food delivery riders. By distinguishing suitability from exposure, the framework moves beyond aggregate scoring toward a more decision-oriented interpretation of street performance.

Applied to a central urban area of Nanjing, the results reveal that high delivery demand does not necessarily coincide with high spatial suitability. Streets with similar overall scores were shown to exhibit fundamentally different internal structures, underscoring the importance of indicator-level diagnostics in identifying safety deficits, efficiency bottlenecks, and adaptability constraints.

By linking evaluation results with exposure analysis and case-based illustration, the study demonstrates how quantitative assessment can support targeted, low-intensity street improvement strategies. The framework is transferable to other high-density urban contexts and provides a practical tool for integrating delivery riders' needs into street evaluation and improvement processes. Although this study focuses on delivery riders, the proposed low-intensity improvements (e. g., organized curbside stopping, entrance interface optimization, and environmental support) can also reduce random stopping and curbside conflicts, potentially benefiting pedestrians and cyclists. Future work should further assess possible trade-offs and synergies among user groups to support more inclusive street improvement.

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Readiness and Adaptation Impact of Road Networks to Automated Driving: Developing an Index as a Tool for More Equitable Development in Rural Ireland with County Roscommon as Case Study

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Abstract: Current research on autonomous vehicle technology (AV), its deployment and advantages, mostly focuses on deep learning, connected vehicles, and their benefits in heavily urbanised areas and megalopolis. This accent on the urban environment and its constant update inevitably leaves out rural areas, gradually creating an ever-widening gap that might become impossible to fill. At the same time, research on AV infrastructure readiness only looks at technical requirements, without considering social or environmental factors. The purpose of this study is to develop a composite Automated Driveability Index (ADI) that integrates social and landscape character metrics through a multi criteria GIS analysis of rural road networks, with Ireland as a case study. The proposed index sets to assess AV deployment readiness in the rural context, but also to bridge the planning gap between the urban and the rural scale by understanding infrastructure capacity and adaptation impacts. Finally, the ADI not only seeks to comprehensively reflect the current state of road infrastructure, but also to serve as a tool for a more just and equitable infrastructure and landscape development.

Keywords: Autonomous vehicles, rural infrastructure planning, composite index, infrastructure readiness.

1 Introduction

1.1 Background and Knowledge Gaps

Technology development and its appearance in our daily lives usually takes the form of "smart" labelled devices and services, wireless and fast connections; all elements that contribute to the idea of Smart City (CUGURULLO et al. 2021). However, it is rare to see and understand the connection between what makes the built environment "smart" and the infrastructural requirements that allow the technology to work. The hardware necessary for cities or other environments to work is often overlooked and its design taken as a technical constraint (RICHARD SENNETT 2020), resulting in priority being given to machines instead of people in most cases. An excellent example of this is how the advent of cars has shaped roads and street life in cities to facilitate their circulation, at the expense of other street users (DUARTE & Ratti 2018, KORNHAUSER & SENA 2024). The starting point of this paper is understanding the role of transportation in the physical and social dimension of planning; particularly, the introduction of autonomous and interconnected vehicles (AV) as what is argued to be the seventh transport revolution (CASCETTA & HENKE 2023). Autonomous vehicles and their degree of automation are defined and divided into six categories by the Society of Automated Engineers; each category is defined by the moment in which the driving task is shifted back to a human (S. A. E. (Society of Automated Engineers) 2021). AV with up to

Journal of Digital Landscape Architecture, 11-2026, pp. 1033-1040. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-770-0, ISSN 2367-4253, doi:10.14627/537770097.

level 3 (L3) of driving automation have already entered the market in the form of assisted driving technology. L4 and L5 are gradually being implemented thanks to both industry pressure and investment, and more collaborative living laboratories between local authorities and research institutions (TAGLIAZUCCHI et al. 2021), despite facing legal and ethical issues due to AI liability. From a technical point of view, the literature extensively investigates AVs' environmental perception, system failure (FAVARÒ et al. 2018, GARCIA & CAMACHO-TORREGROSA 2020), and decision-making (ACHEAMPONG & CUGURULLO 2019, and references therein, ROBINSON et al. 2022). This research aims to identify areas of technological improvement and the potential of neural networks for Vehicle-to-everything communication technology (V2X). Studies recognise some limitations in the way AV technology detects the road environment, like its ability to read lane markings depending on the contrast between Light Reflectance Values (LRV) of the marking itself and the asphalt colour (YAO et al. 2025). These technical limitations are gradually finding their way into road requirements and road design regulations, especially if a city is interested in acquiring the "smart" label (OFFICIAL JOURNAL OF THE EUROPEAN UNION 2021).

Requirements such as the UN regulation on Automated Lane Keeping systems, or the Italian Smart Road Decree (ITALIAN MINISTRY OF INFRASTRUCTURE AND TRANSPORT 2018) and similar hard specifications represent a way of designing our transport network that prioritises technology's needs, instead of societal or environmental ones. In turn, this highlights a critical lacuna in the literature: the quantitative linkage between the measurable, physical properties of existing, non-Smart infrastructure and actual AV operational readiness. Traditional infrastructure metrics (e. g., Pavement Condition Index) fail to capture the multi-dimensional environmental complexities that merge technical with societal and environmental needs. Furthermore, while the impact on city and street liveability is being explored, the rural environment is overlooked. Rural, peri-urban and peripheral communities often rely on older, regional road networks, and the effect of infrastructure upgrading (or lack thereof) on their social capital and economic connectivity is under-theorised. This persists despite studies highlighting a strong relationship between transport poverty and economic opportunities (KELLY et al. 2023).

This paper addresses this critical node by developing, introducing and applying a composite indicator that seeks to objectively quantify the suitability of road networks for highly automated driving. The purpose of this Automated Driveability Index (ADI) is not just to assess the state of a single stretch of road or a road network, but also to provide key insights to potential adaptation strategies and impact scenarios. The index is interpreted also as a tool for planning and infrastructure development, as it creates a connection between abstract technology requirements and performance and the built environment. The case study chosen for this is a rural road network in Ireland, where the landscape of small towns and the importance of connections between them makes it a valuable example.

1.2 Structure and Purpose of this Study

The purpose of the paper is to establish the basis for understanding rural infrastructure readiness for AV deployment, to then assess the potential societal and environmental impact of road adaptation to bridge the gap between technology requirement and reality.

Including the introduction, the paper is divided into three sections. The second section develops a theoretical framework and list of datasets necessary to develop the driveability index.

The methodology also focuses on selecting as a case study a county in Ireland, to conduct a GIS suitability analysis of the local road network, considering assumptions and limitations of currently available open datasets. The third section looks at the results of the analysis, evaluating the overall readiness of the case study for AV implementation. This section also discusses the possible outcomes of road adaptation impact through different scenarios that allow to understand how the ADI index can be used as a tool not only for policy makers, but also for infrastructure and landscape designers. The conclusion section further expands on research that could be carried out with more in-depth analysis and more extensive primary data collection on landscape character and road environment, in the context of a living lab.

Finally, this study seeks to highlight the link between technology development, infrastructure, mobility and car-dependency, and landscape development and design, with a focus on Irish rural areas. The purpose of this research is not just to establish a framework for a comprehensive readiness and adaptation impact assessment, but also to show how a composite index can be used as a tool for equitable landscape development and policy making in areas in which the smart city approach cannot be considered a viable option. Beyond its technical application, the research is framed within a broader discussion on the profound social and environmental implications inherent in the act of designing infrastructure for technology, arguing that every design decision is an implicit policy choice with measurable societal consequences.

2 Methodology

2.1 Building the Composite Index

Here we develop the Autonomous Driveability Index as a scalable, quantifiable tool to assess infrastructure suitability of existing roads to L4/5 automation, which the Society for Automated Engineers defines as the systems that do not revert decisions back to a human driver in case of failure (Engineers 2021). The composite index relies on physical and social indicators that reflect the condition of a given stretch of road, to assess its readiness for AV deployment. All technical values and suitability scores are based on the literature cited in chapter 1.1.

For road metrics, parameters have been selected following environment perception literature and separated into three categories: road conditions, weather conditions, and traffic related issues. The first determine AV ability to read and understand the environment, therefore representing a major portion of the ADI to be developed. The second can heavily impact AV performance in case of unpredictable events, but they do not necessarily occur regularly, or with high frequency. Traffic related issues increase the risk of unavoidable accidents, especially the ones in which a constraint of space availability does not allow to avoid collisions.

Some of these parameters, such as lane width, are more linked to vehicle dimensions and characteristics than to technology and sensors themselves, while some of the metrics are calibrated specifically for Ireland and are based on weather data and the Corine Landcover. For example, it is known that unexpected road obstructions such as branches can be a trigger for system disengagement (FAVARÒ et al. 2018) therefore we consider that roads within a small distance from forests or treelines, and which are likely to be exposed frequently to strong winds, would score lower in the suitability assessment of road environment.

On the other hand, social metrics look at the potential deployment of AV within the public transport framework. Though more could be integrated in future research, the ones chosen for this paper rely on population distribution through building mapping, and infrastructure coverage between main towns. In the context of the current study, AV deployment with L4/5 automation is being looked at from the point of view of a dynamic public transport network and system rather than private vehicles, for two main reasons. First, research on social acceptance and potential use of automated driving and on the current European planning context shows that AV are more likely to be deployed by local authorities, and accepted by citizens, as part of public transport schemes (CUGURULLO et al. 2021). Second, the EU Artificial Intelligence Act (2021) has not yet completely bridged the gap between ethical issues and the laws necessary to operate fully automated vehicles, which puts market penetration from the private car industry at a disadvantage.

The parameters are all weighted against each other following the Analytic Hierarchic Process (SAATY 1987), a method used to establish priority between metrics that cannot be compared directly with each other by assigning 1-9 importance scores. The scores are used to build a normalised matrix which in multiplying factors that establish each metric's impact on the final ADI score. The index is therefore calculated as a weighted sum of all criteria and can be interpreted as a suitability assessment from which policies and strategies can be developed. The geospatial analysis is carried out with Geographic Information System (GIS) tools, specifically with an ArcGIS model builder. The analysis sequence starts with assigning 1-3 suitability scores to datasets, based on their attributes; all scores are collected into a single through a Fishnet with 50x50 m tiles – found to be a good resolution to gather significant results on a county scale. This, intersected with the road network layer, results in a high-resolution map (Fig. 1) of automated driving readiness that not only highlights specific segments of infrastructure deficit but also allows to isolate the main causes of lower scores and therefore plan an appropriate course of action.

2.2 Case Study: County Roscommon

Considering the limitations of this study and the margin of error given to assumptions to fill the gaps in available datasets – more clearly explained in the following section – a choice has been made to analyse a single county in Ireland. The county scale reduces the number of roads and towns included, it simplifies the system dynamics and the infrastructure metabolism, also avoiding error accumulation and incorrect data interpretation. In the Midland region, Roscommon provides a relevant rural case study, especially in the transportation planning framework, as it also scores low when analysed through the Transport Poverty Risk Index (TPRI), a composite spatial indicator designed to capture transport-related disadvantage by bringing together measures of affordability, accessibility, and mobility at Small Area level. The index draws on census and publicly available data, combining indicators such as transport and fuel costs, access to essential services and public transport, and prevailing travel behaviours into a single measure of transport poverty risk using a weighting framework (KELLY et al. 2023). Applied to the 2016 Census dataset, Roscommon records an overall TPRI profile that places the county in the upper range nationally, indicating that transport-related disadvantage is more pronounced than in much of the state. What is key is that these transport poverty related characteristics are observed across most Small Areas in Roscommon rather than being confined to a small number of locations, suggesting that transport poverty risk is structural and widespread. This context is important when thinking about road adaptation and automated driving in rural areas, as infrastructure decisions can either help to

improve access to services or, if poorly targeted, further lock communities into car dependency and existing inequalities.

2.3 Data Sourcing, Limitations and Assumptions

The study has been carried out entirely through available open data and information published online by Irish Transport authorities, which have allowed some assumptions to be made based on national data to fill the gaps encountered. The spatial analysis relies then on secondary data. Hence, data availability and time constraints must be considered the main limitation faced in this research. Though the metrics has been informed by the literature, not all datasets necessary to carry out a full assessment are available open data. Where data were absent, assumptions have been made based on information contained in documents relating to or diffused by Transport Infrastructure Ireland (TII), and on road classification (national, regional, local, etc.). Due to the restricted time, the use of AI as an enhanced researcher (Perplexity, Gemini) has been instrumental in gathering and summarizing information distributed across different sources made available by governmental bodies and other official Irish authorities. All sources have been manually verified.

In full consideration and awareness of this study's limitations, the datasets integrated in this analysis are deemed sufficient to draw insightful conclusions on how to assess infrastructure readiness for autonomous driving and subsequent considerations on adaptation impact. Further studies and publications will be developed to expand on primary data collection and elaboration for a more comprehensive and accurate index.

3 Results and Conclusions

This section presents the results of the analysis, both in the form of a map and a chart, and it links them to the policy making and intervention framework, showing with clear example the deployment of the ADI as a decision-making tool.

The main result of the study is the map in Fig. 1, in which red to green colour coding shows road scoring. The 50x50m tile resolution allows clear reading at the county scale, but it also captures the lack of continuity of some scores across the same stretch of road. Visually, the map results in higher scores towards the North of the county; this is due to the influence of the "Town Coverage" parameter, which scores high thanks to the proximity between the towns of Roscommon, Elphin, Frenchpark, Carrick-on-Shannon. Though towns and roads outside of the study area boundaries have been integrated in the Service Area Layer calculation, other relevant towns appear to be too far between each other to influence the ADI score. In the county's South, Athlone and Ballinasloe appear quite isolated from the rest, indicating their more relevant connection to Galway, in the West of Ireland. The absence of relevant bus routes between Roscommon and Athlone has also affected the score. From a policy making point of view, this result could potentially be a trigger for a census analysis of commuting flow and job market to understand whether better connections between the two towns would, in fact, be needed. Though this does not strictly apply to AV implementation, it is an example of how the ADI may be used as an insightful tool for decision making. Smaller roads appear fragmented, especially in the North-East area, where the nature of the soil and the data from the landcover dataset makes it more prone to flooding and, therefore, it is judged less suitable for safe automated driving.

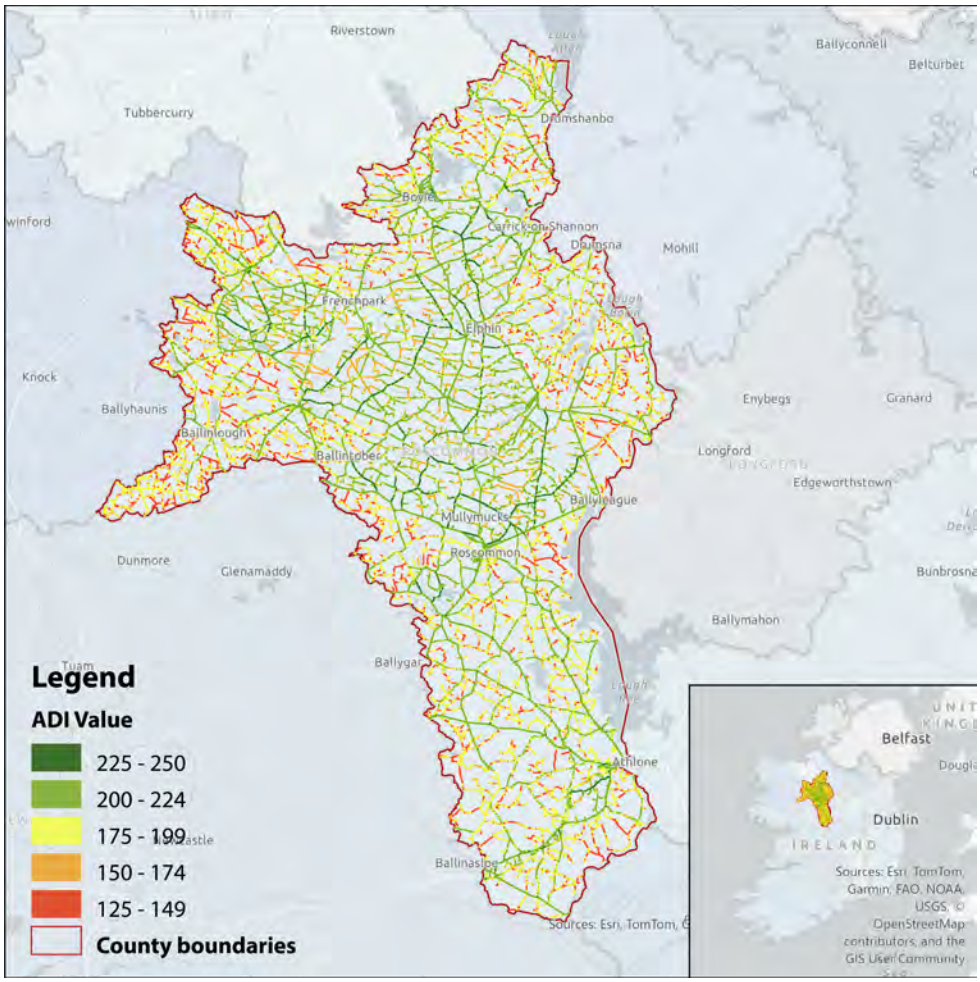

Fig. 1: Colour coded results of the GIS analysis for County Roscommon road network

Overall and considering the assumptions made by road classification, the results can be analysed through this categorisation as well (Fig. 2). Chart values are the averaged sum of all scores by metrics category, considering every stretch of road belonging to the same road class. The highest overall scoring is found in Local Primary roads (L-roads). These are key public roads, wider than 4 m, which carry important local traffic, though they are more relevant at the county scale and they are not as overloaded as regional roads. In terms of the chart results, what is key is the fact that L-roads do not necessarily score higher than others – road conditions are worse than on national secondary roads, which could potentially be faster connections between towns – but they are the ones with the most consistent score. The relevance of this lies in the fact that L-roads are potentially ready for immediate AV implementation. Local authorities may consider L-roads as valuable testing ground for automated public transport on a county scale, possibly in the context of a living laboratory, where industry and research get also involved in the development of the most appropriate driving technology. As

a result, local roads may become the focus of future development or change. Without careful consideration from planning authorities, local roads may be subject to specific improvements, possibly relating to asphalt markings, lane expansion, lighting, or other safety measures dictated by current and future LiDAR technology. The core finding is that an unmanaged transition, driven purely by technical feasibility, is highly likely to reproduce and magnify existing socio-spatial inequities, creating segregated mobility landscapes.

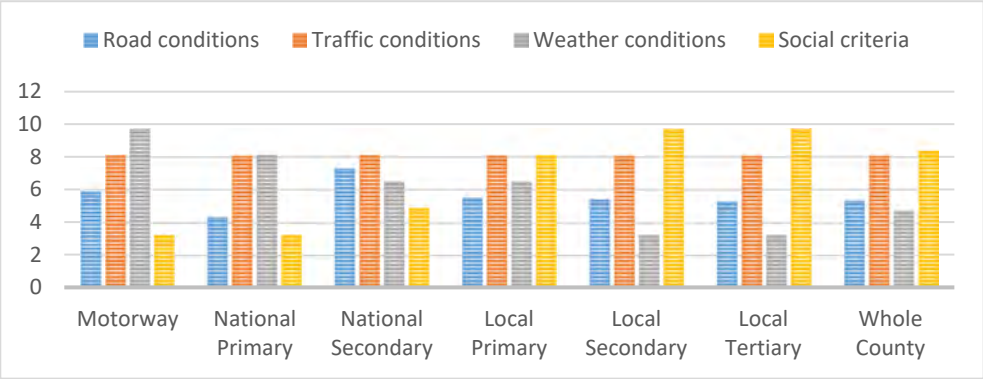

Fig. 2: Normalised average score of each criteria category, by road classification and for the whole Roscommon County

The Autonomous Driveability Index (ADI) provides a necessary quantitative foundation for assessing the complex task of integrating highly automated mobility into existing and varied road networks, while ensuring that the proper impact assessments are undertaken. The paper argues for a Socio-Technical Design Approach, where the ADI is used not merely to flag problems, but to prioritize development based on both technical need and social equity. This requires a shift in infrastructure philosophy: ensuring that road upgrades for automation also align with broader goals of sustainable liveability, local employment, community integration, and landscape character, rather than solely facilitating the vehicle's technological performance.

Further studies derived from this paper and other related research should focus not only on improving our knowledge of the current state of roads and transport infrastructure, but also on expanding the ADI to integrate social readiness factors, such as public perception and community preparedness for technological change, into a holistic Societal Automated Driveability Index (SADI), ensuring that infrastructure design serves not only the autonomous machine but, fundamentally, the human community.

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Accessing Idiosyncratic Modeling under Constraints in Landscape Architecture

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Abstract: Confronted by intertwined socio-ecological crises, landscape architecture must engage with increasing complexity through deeply site-specific, or idiosyncratic, approaches. Digital tools hold significant potential for this task. This paper argues that a site-specific design approach, operationalized through idiosyncratic modeling, is a crucial pedagogical strategy. However, its integration into education remains uneven, often attributed to constraints like limited time, software access, and equipment. This paper posits that the primary barrier is not tool inaccessibility but a lack of methodological scaffolding. Using a design studio at TU Wien with an integrated workshop at Seoul SNU as a case study, we demonstrate a replicable, lean pedagogical framework for teaching site-specific design via idiosyncratic modeling under constrained conditions. The framework employs open-source software and data, photogrammetry through personal fieldwork, and a flipped-classroom model. Results show that students with heterogeneous prior knowledge can achieve precise, site-analytical design outcomes and successfully transfer methodological knowledge to peers in a cross-cultural workshop. The study concludes that this approach democratizes advanced digital design thinking, enabling contextual sensitivity and typological experimentation irrespective of institutional resources.

Keywords: Digital landscape architecture pedagogy, idiosyncratic modeling, site-specific design, personal remote sensing, lean pedagogy, open-source tools

1 Introduction

The climate and biodiversity crises demand a socio-ecological transformation in which landscape architecture must play a key role. This requires engaging with the dynamic entanglements of human and more-than-human worlds and the specific materiality of the Earth's critical zone (LATOUR 2018). To navigate this complexity, the discipline increasingly turns to digital tools. However, the critical challenge lies not in technology adoption but in its reflective integration into design thinking. Tools should function as epistemic instruments – extending cognition, enabling precise site-specific understanding, and informing design synthesis (MALININ 2016). This is particularly vital in urban landscapes, where interventions must respond to highly particular, or idiosyncratic, environmental and cultural conditions.

We adopt Landscape Topology as a guiding design attitude grounded in site-specific intelligence (GIROT 2013). It promotes an active dialogue between existing site conditions and transformative intentions. Through typological transfer, we aim to generate new creations that move beyond the status quo. To achieve this transfer within a topological stance, we employ three-dimensional models not as neutral abstractions, but as mediating devices to interpret and articulate aesthetic qualities of the site in relation to design intent. Their value lies in preserving specificity while enabling creative exploration, ensuring that design decisions remain anchored in the physical and spatial realities of place.

When understood epistemically, three-dimensional precision modeling functions not as a tool for visual realism but as a cognitive apparatus for engaging with situated conditions (URECH

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et al. 2022). Beyond generic, parametric or abstract 3D modeling, *idiosyncratic modeling* denotes a modeling mode in which geometric structures, scalar relations, and spatial parameters are derived from empirically grounded survey technologies – such as remote sensing, photogrammetry, or LiDAR – and remain explicitly tied to the physical realities they surrogate. Rather than prioritizing visual plausibility, survey data preserves epistemic traceability: measurements remain legible, uncertainties identifiable, and abstractions accountable to their sources. This distinguishes idiosyncratic modeling from photorealistic or speculative reconstructions common in computer vision and visualization, which may generate convincing forms while severing links to measurable reality.

Despite its potential, the integration of advanced digital methods into landscape architecture curricula is uneven. This unevenness is often mistakenly attributed to material constraints limited teaching time, lack of software, or absence of advanced equipment. Also limited faculty capacity to invest in mastering new technological paradigms causes methodological lock-in with familiar design approaches (PLATER 1995). Consequently, site-specific design is frequently regarded as exclusive, fostering conceptual imprecision at a time when rigorous engagement with each site is needed to prevent homogenization of landscape aesthetics. A practice of idiosyncratic modeling could improve design attitude toward landscape and urban Baukultur, enabling models to function as instruments for reasoning about identity and aesthetics.

We argue that this unevenness is instead closely linked to how access to advanced digital education is paved. This paper investigates whether site-specific design can be effectively operationalized under "lean" pedagogical conditions. Using a design research studio as a live demonstrator, our research questions are: (RQ1) *Feasibility*: Can idiosyncratic modeling be effectively taught using only standard laptops, personal cameras, open-source data and software, and within a compressed schedule to students with varied prior knowledge? (RQ2) *Transferability*: Can the core methodological principles be transferred by students to peers across different institutional contexts? By addressing these questions, we position idiosyncratic modeling not as an exclusive process but as a democratizable practice. We demonstrate a pedagogical framework that turns constraints into a proof of concept for wider accessibility, fostering a digital literacy for topological design attitude.

2 Methodology

The research was conducted as a single case study following qualitative case study methodology, in which a specific educational setting is examined to gain insight into a broader pedagogical question. The case selected was the design studio Making Greenways – A Typological Transposition between Vienna and Seoul, held at TU Wien between October 2024 and January 2025 (URECH & AHN 2025). The studio involved sixteen students from architecture and spatial planning programmes at both Bachelor's and Master's levels, exhibiting heterogeneous prior experience with digital tools and three-dimensional modeling.

A mixed-methods evaluation strategy was employed to assess both the feasibility and transferability of the proposed pedagogical framework. (1) Participant observation was conducted throughout tutorials, fieldwork sessions, and workshops in order to document student engagement, problem-solving strategies, and difficulties encountered during the modeling process. (2) Design outputs were systematically reviewed to evaluate the degree of site-specific-

ity, geometric precision, and creative differentiation achieved through idiosyncratic modeling. Observational data and design output were captured, analytically reflected and organized according to thematic correspondences and recurring patterns across projects. (3) The study further analyzed the outcomes of a two-day peer-teaching workshop to address the question of methodological transferability in which students from TU Wien introduced the core modeling workflow to peers from Seoul National University. The effectiveness of knowledge transfer was assessed through the quality and completeness of the resulting models and through observation of collaborative workflows. (4) Finally, reflective dialogue was examined through informal student feedback during the course and through formal course evaluation surveys, providing insight into perceived learning outcomes, challenges, and the accessibility of the methods under constrained conditions.

3 Case Study: Implementing a Lean Pedagogical Framework

3.1 Design Task

The design studio focused on the transformation of the Wien River, currently configured as a highly engineered flood channel that nearly reached its flow capacity during storm Boris in September 2024, into a multifunctional green corridor. Sixteen students were tasked with developing proposals in groups that enhance flood resilience, improve microclimatic performance, and expand recreational and ecological functions. Central to the assignment was a typological transposition, whereby students critically engaged with international precedents – most notably the Cheonggyecheon restoration in Seoul – to adopt underlying typological principles to the specific hydrological, spatial, and cultural conditions of the Viennese context.

This framing emphasized the design attitude. It distinguished between a model for copying and a type for transformation, positioning the design task as a critical reinterpretation of formal structures rather than their replication (MONEO 1978). This approach deliberately steered the creative repertoire away from producing deceptive imitations of an idealized nature and toward functional and technical honesty (AHN & KELLER 2016). To liberate the design process from preconceived solutions, the workflow combined the site-specific approach with generative overlay sketching and collage. This encouraged intuitive exploration through making, aiming to develop an adaptive design process itself (LEE 2016).

3.2 The Idiosyncratic Modeling Workflow

To operationalize the design task with the intended theoretical stance, students were guided through a workflow for idiosyncratic modeling (Figure 1). The workflow structures design activity through successive tasks of grounding, forming, and testing, using the digital site model as a mediating device between empirical site data and design creativity. The workflow uses LiDAR data, which is distributed around the world with standard specification in *.LAS or *.LAZ formats. Preprocessing the initial LiDAR data into a workable point cloud model can be directly delegated to the students, which is usually limited to downloading, merging, segmenting and coloring. In rare occasions, higher expertise is required for denoising and classifying raw LiDAR datasets.

Design grounding involved digitizing the site as geometric documentation to inform the design process. Through registration, geolocation, and segmentation, photogrammetric models built from photographic field surveys were combined with publicly available aerial LiDAR datasets. Survey data were thus transformed into a three-dimensional model with epistemic value, enabling students to develop their spatial hypotheses within empirically grounded measurements.

Design forming focused on the selective extraction and transformation of site data to generate new spatial concepts. Design intentions were articulated through overlay sketching and digital collage using a typological library of self-collected elements. The aerial point-cloud model provided by the City of Vienna, including semantic classification, was filtered to isolate ground points. These points were rasterized into depth maps, that is, grey-scale images that students were able to manipulate with familiar image editing software. Normalization, defined as the subtraction or addition of the depth map elevation to a point cloud model, aligned typological elements with modified topographic conditions. This ensured that design operations remained grounded in the underlying logic of the terrain.

Design testing centered on communicating and evaluating design proposals through an altered site model. Visualization and calculation techniques repeatedly tested assemblies of existing **and** new fragments at true scale, establishing a hybrid dialogue between site realities and prospective inventions. Time permitting, the 3D-explicit altered model could support further exploration of complex dynamic phenomena, enabling science-design feedback loops with iterative refinement grounded in physically validated simulations.

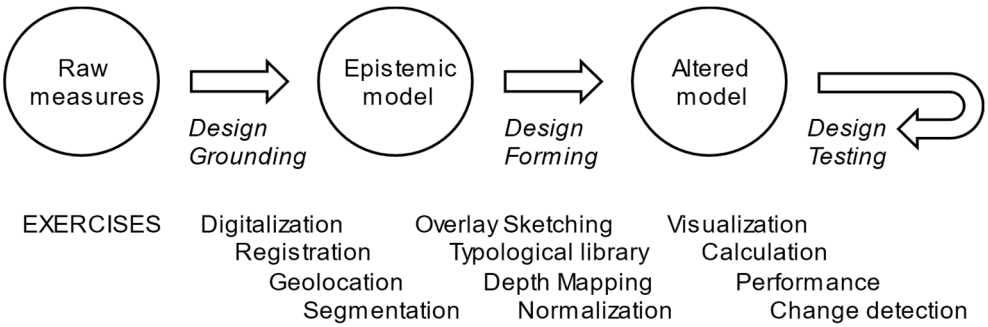

Fig. 1: Workflow illustrating how design grounding, forming, and testing operate as successive transformations of a shared digital site model, enabling idiosyncratic modeling from documentation and prospective transformation to performance-based evaluation

3.3 Pedagogical Implementation for Lean Conditions

The pedagogical framework was explicitly designed to operate under lean conditions characterized by limited contact hours, heterogeneous prior competencies, and the absence of specialized infrastructure. Rather than distributing technical content across extensive instruction, access to idiosyncratic modeling was achieved through a sequence of concise, interdependent exercises (Figure 1). Each exercise combined a bounded task with a theoretical question, allowing technical and conceptual understanding to emerge simultaneously. Beyond the

studio, a two-day exchange workshop in Seoul implemented a digitalization and collage exercise, in which students collaboratively experimented with spatial compositions.

This exercise-based structure functioned as a form of methodological scaffolding (LIN 2024). By constraining the scope of each task, students were able to engage with complex design reasoning without requiring comprehensive prior tool mastery. Modeling literacy was not taught as abstract skill but encountered as necessary means to articulate site definition, spatial relevance, typological transformation, or topographic intent. In this way, the studio time was reserved for conceptual development and collective reviews, while learning progressed largely through personal making and peer exchange. Under these lean conditions, idiosyncratic modeling became accessible not through resource intensity, but through pedagogical sequencing that led each group to produce a comprehensive proposal (Figure 2).

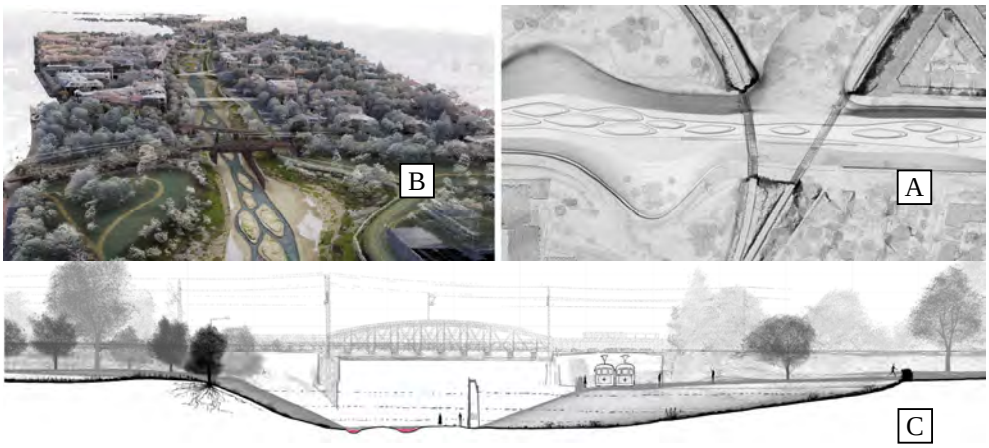

Fig. 2: River corridor proposal balancing ecological restoration with urban accessibility, illustrated in plan, section and perspective using an altered point cloud model as base. This proposal introduced meanders that were topographically modeled from the LiDAR survey to improve habitat diversity and control runoff along the river (A). The existing linear drain was graded to make room for vegetation and allow people to access the river landscape (B). Existing infrastructure, such as bridges and side roads, was integrated in the design proposal providing a topographically seamless resolve (C).

3.4 Material, Methodological and Cognitive Access

Material access was given to students through open-source, cross-platform software, enabling use on standard personal laptops without licensing or institutional dependencies. Publicly available spatial datasets of Vienna, such as mobile Kappazunder and aerial LiDAR data, were combined with personally collected survey data, ensuring that all inputs could be obtained and processed independently. Software not originally developed for design practice – such as Meshroom, CloudCompare, and QGIS – was introduced through the exercises.

Methodological access was provided through a curated collection of short video tutorials accompanying the research (URECH 2026). Crucially, all tutorials were subtitled and kept under ten minutes, focusing on the steps required for each exercise and allowing students to

grasp the overall workflow while progressing at their own pace. This combination of reproducible workflows and task-specific instruction enabled cognitive access by supporting students in operating software and data within a design-reasoning context. It allowed students to complete all exercises independently, producing site-specific proposals without requiring prior technical expertise or access to specialized infrastructure.

4 Results

4.1 Achieving Site-Specific Precision under Lean Conditions (RQ1)

Feasibility was documented through participant observation, comparative analysis of studio outputs, and student feedback. Observation of design development and final presentations showed that students were able to address demanding design challenges along the river corridor, including cross-scale coordination with centimetric design precision, differentiated spatial transitions, and the integration of hydrological and ecological logics within a coherent design concept. Notably, an observed pattern early in the semester was transformative reticence; several students, initially overwhelmed by the high-resolution LiDAR data, proposed only minor modifications or additive elements rather than the determinate transformations the task required. Through weekly supervision and technical scaffolding, this hesitation was gradually replaced by more confident, integrated proposals. Projects reacted to existing conditions rather than relying on abstract heuristics, supporting site-specific differentiation along the river.

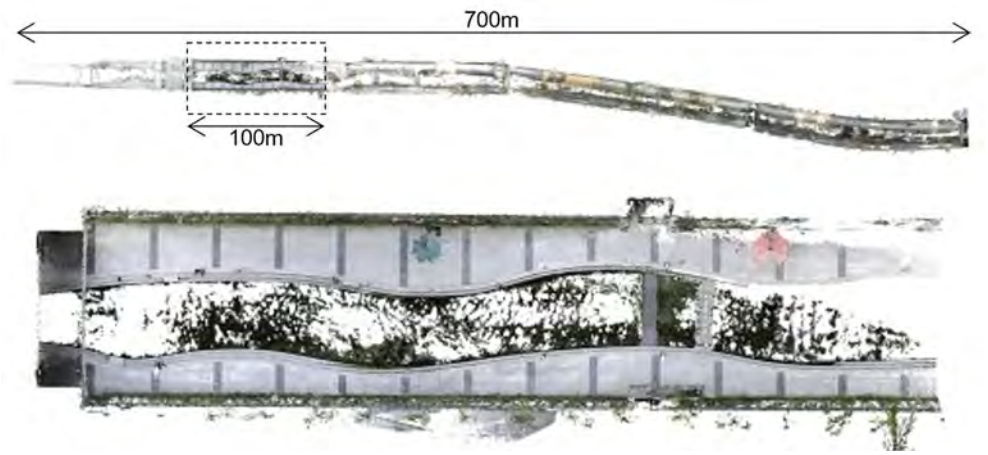

Fig. 3: Since no public 3D data was available in Seoul, the 32 workshop participants collaboratively digitized the first 700 m of the Cheonggyecheon River using photogrammetry. Segments of the resulting model served as fragments for the typological library.

Studio outputs demonstrated a precise handling of terrain as a design medium, with outcomes being idiosyncratic to the sites through seamless integration of existing and new terrain. Proposals were developed through a typological library derived from personally digitized spatial elements (Figure 3), which supported consistent placement of vegetation and built elements

across scales. By the end of the semester, each group assembled a complete, spatially positioned model of their proposal that seamlessly integrated existing and newly designed terrain (URECH et al. 2025). Student feedback confirmed substantial gains in methodological confidence – a shift from procedural uncertainty to topological agency. This motivated several participants to further develop the approach in thesis projects.

4.2 Transferability and Peer Teaching (RQ2)

Transferability was examined through a two-day cross-institutional workshop at Seoul National University, where students from TU Wien and SNU collaboratively explored typological transposition through a collage exercise. Groups were tasked with imagining a fictional urban space that is welcoming to both human and non-human agents, integrating surfaces, amenities, and topographies that encourage visitation and stay. The exercise emphasized creative experimentation while maintaining a structured approach to spatial reasoning. Results showed that students unfamiliar with the workflow were able to adopt the underlying modeling logic within the short timeframe and apply it to a new cultural and spatial context. Learning relied on the sequential, exercise-based structure rather than prior digital literacy, and peer teaching allowed methodological knowledge to be externalized and reinforced. The activity demonstrated that idiosyncratic modeling can be transferred effectively when framed as a series of decisions grounded in design reasoning.

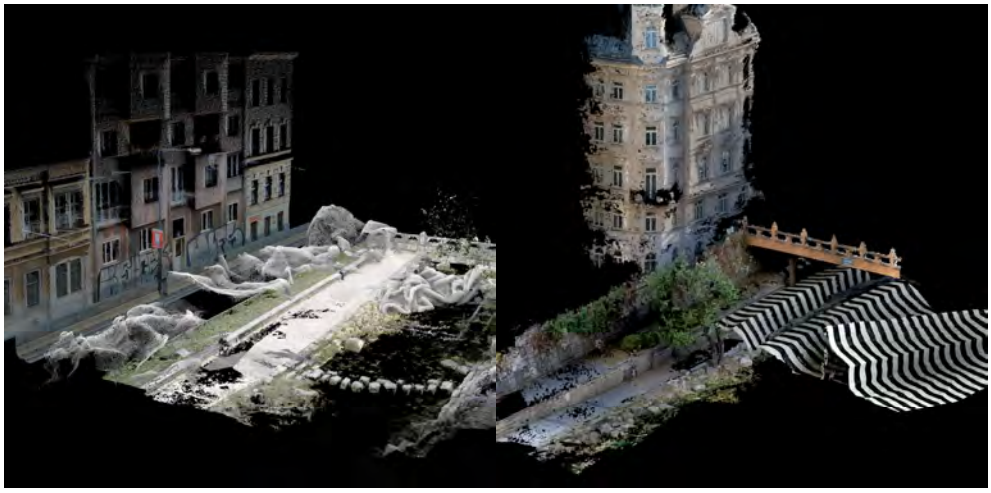

Fig. 4: Collage of typological elements combining three digitized sources: a laser-scanned fragment of Vienna, a segment of the Cheonggyecheon River and a manually fabricated scale model, both digitized with photogrammetry. Shown perspectives are screen captures from 3D models presented live during the workshop, illustrating spatial qualities, surfaces, and topographies.

Reflective feedback further clarified the conditions of transfer. Participants reported that producing their own survey data substantially deepened spatial understanding compared to working from supplied representations. The flipped-classroom structure reduced technical hesitation and enabled studio time to focus on design reasoning. Several students expressed

motivation to extend the method into thesis work, indicating sustained engagement. Reported challenges included software compatibility across operating systems and the linearity of certain workflows, which occasionally constrained iterative exploration.

5 Discussion and Conclusion

5.1 Feasibility Under Lean Conditions

The case study demonstrates that site-specific design through idiosyncratic modeling can be taught effectively under lean conditions by providing critical access. Participants with limited prior experience in landscape architecture were able to leverage contextual intelligence. The workflow was sufficiently intuitive for students to adopt methods that function independently of institutional resources and develop a shared vision of Vienna, visually embodying the collective, topological design outcome (Figure 5). The method emphasizes design judgment and creative reasoning, framing computational processes as instruments for exploration rather than technical ends. Limitations arose from software differences between operating systems and the linearity of workflows, which constrained iterative experimentation. Nevertheless, the project shows that methodological scaffolding, rather than resource abundance, enables meaningful engagement and mastery of site-specific design.

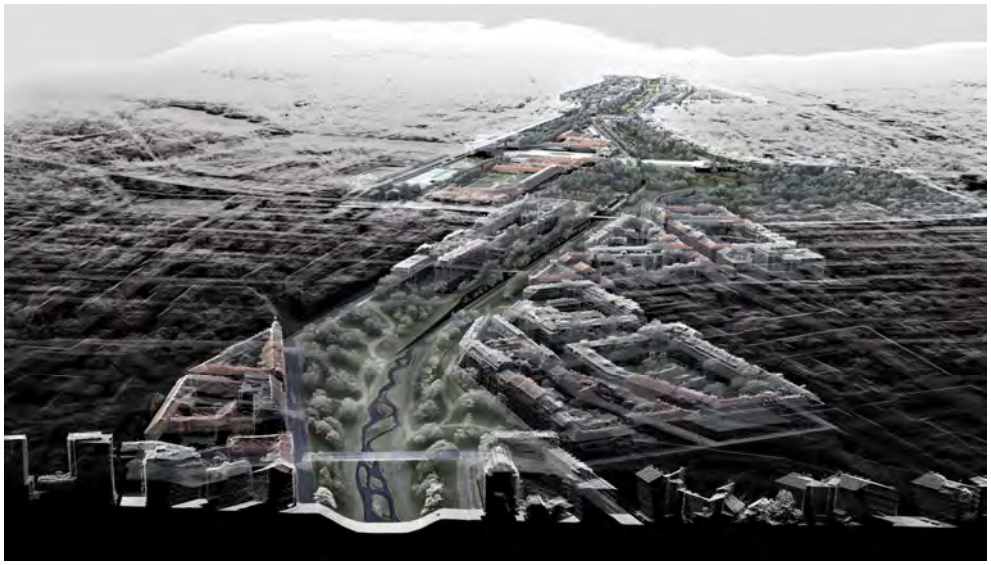

Fig. 5: Composite proposal for the Vienna River restoration, illustrated here as section-perspective from Untermeidling to Hietzing. Each student group designed a segment along the final 10 km urban stretch and within the 30 m elevation range, transforming and reassembling raw survey data into an altered, geolocated 3D point-cloud model. Intervention perimeters, segmented as “river space” and illustrated in color, enable seamless integration of all proposals into the city’s aerial LiDAR dataset illustrated in greyscale.

5.2 Transferability Across Contexts

The cross-institutional workshop in Seoul demonstrates that topological design principles can be effectively adapted across educational and cultural contexts. In culturally specific settings, the approach highlighted subtle local characteristics, enabling designers to reflect holistically on building culture. Typological transpositions align with the manipulation of components whose significance emerges not in isolation but through their integration into a coherent whole (LAWSON 2006, 54-61). Transposition became legible through the creation of dedicated object libraries, fostering creative reflection on the contextual rationale behind spatial elements. Limitations include the continued need for skilled instruction and structured guidance, as students tended to revert to familiar CAD workflows when hesitant with point cloud models. The study remains constrained by a single-case design and a small sample (16 students from TU Wien, 16 from SNU), suggesting broader research is needed to generalize results.

5.3 Conclusion: From Constraints to Democratization

This study positions lean conditions not as a deficit but as a productive pedagogical driver. Rather than relying on technological abundance, the presented framework demonstrates how situated design and idiosyncratic modeling can operate through selective precision, judgment, and interpretive agency. In doing so, it reframes advanced digital design not as an exclusive competence tied to infrastructure or expertise, but as a form of literacy that can be cultivated through access to data, methods, and conceptual structures. In line with FRICKER et al. (2024), computational processes are mobilized not for technical optimization but to expand the space of design inquiry beyond immediate human intuition. By foregrounding transferability, judgment, and collective authorship, the framework advances a democratized understanding of digital landscape design that is adaptable, culturally responsive, and critically grounded in site-specific transformation.

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A Decade of Geodesign Pedagogy: Advancing Multiscale Digital Planning Through Studio Practice

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Abstract: Geodesign has become an increasingly important framework for integrating analysis, design, and collaboration in higher education across landscape architecture, urban planning, and related design disciplines. This paper examines the evolution of geodesign pedagogy through a comparative analysis of four Studio projects conducted between 2018 and 2025, three in Georgia and one in Iowa (USA). Across these cases, students learned and applied geodesign concepts and practices, using analytical workflows that incorporate Geographic Information Systems (GIS) and web-based collaborative platforms such as Geodesignhub and ESRI's Geoplanner. A comparative review of these case studies led us to discuss various aspects of the learning process, cross-scale reasoning, design, and collaborative engagement. The analysis identifies both pedagogical opportunities and challenges, including coordination across scales, variations in data readiness, and uneven distributions of technical expertise and access to shared analytical workflows. The paper concludes with implications for future geodesign pedagogy in higher education.

Keywords: Geodesign, planning studio, higher education, pedagogy

1 Introduction

Geodesign is a planning collaborative environment that incorporates multiple stakeholders' perspectives, offering a conceptual and procedural framework that links analysis and intervention through scenario-based reasoning, stakeholder modelling, and visualization-supported decision-making. Campagna (2023) provides an alternative definition of geodesign as "a set of techniques and enabling technologies for planning built and natural environments in an integrated process, including project conceptualization, analysis, design specification, stakeholder participation and collaboration, simulation, design alternatives creation and impact evaluation (among other stages). Geodesign applies system-thinking and makes the relationships between design and its geographical context explicit, as the design is dynamically related to a multi-scale digital computational twin of territorial systems."

Building on this theoretical foundation, this paper positions geodesign pedagogy not as a single, linear, fixed instructional model, but as a set of adaptable practices shaped by scale, duration, technical capacity, collaborative structure, and the selection of digital tools. While prior scholarship has documented individual studio or workshop applications of geodesign, fewer studies have systematically compared multiple educational implementations that employ different combinations of GIS-based analytical tools and frameworks (e. g., ArcGIS Pro, LUCIS-based suitability modelling) and web-based collaborative platforms (e. g., Geodesignhub, ESRI GeoPlanner). Drawing on four geodesign-based educational cases conducted between 2018 and 2025, this paper adopts a comparative case approach to examine how variations in scale, group configuration, analytical workflows, and data readiness influence both learning processes and design outcomes. Digital landscape architecture and plan-

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ning education continues evolving to integrate geodesign and geospatial modelling, real-time feedback cycles, iterative design, and cross-disciplinary collaboration.

Multiple frameworks and methods have been developed, with the most prominent and widely known being Steinitz (2012). The Steinitz framework for geodesign entails a three-stage iterative process developed around six foundation models (representation, process, evaluation, change, impact, and decisions), all six building/characterizing the study area, through a series of questions, the evolution, the present, and the future (Fig. 1). The three iterations are intended to follow the six models in different directions, with the first one intended to define the scope of the study (addressing the "Why" question: Why do we need the study, what is the overall problem). It starts with the representation model and concludes with the decision model, which, among other things, helps identify stakeholders. The second iteration is intended to define the methodology, and, with that, a particular focus is placed on understanding stakeholders' decisions by defining the evaluation criteria and weights, assessing the impacts of each action, and finalizing with the identification of data and information needs. And the final iteration is the final implementation, following a more traditional Studio sequence that starts with inventory and data collection (identified in the previous iteration), identifies projects and policies during the change phase, and concludes with evaluation of impacts and decisions.

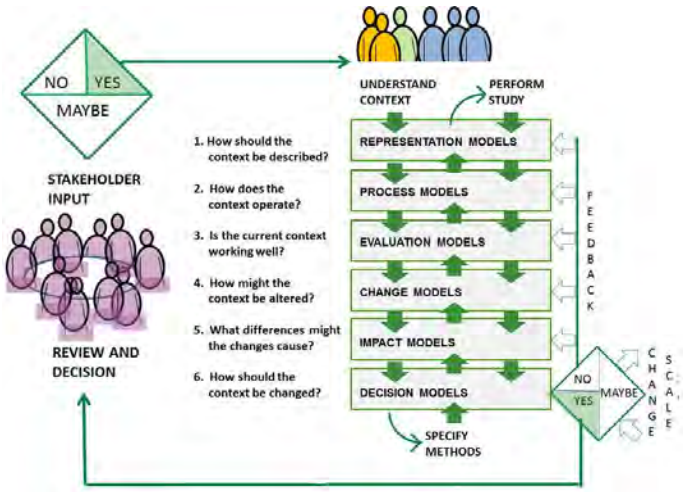

Fig. 1: Geodesign framework for the Georgia Workshop (reprinted from Carl Steinitz)

Another geodesign framework of particular applicability for more experienced GIS users is the LUCIS (Land Use Conflict Identification Strategy) developed at the University of Florida (CARR & ZWICK 2007). This model uses a systems approach to evaluate land suitability from the perspective of different stakeholder interests. In a similar fashion to the Steinitz framework, it starts by formulating the problem at hand and, from there, by considering stakeholders' preferences and values, which guide the suitability modelling process. Topics such as agriculture, conservation, and urban development were initially explored, with other applications that can be tailored depending on the problem. In this context, suitability is understood as a measure of the relative attractiveness of land for a given purpose, derived through

a structured and sequential analytical process (CARR & ZWICK 2007). Rather than predicting specific land-use outcomes, the method identifies areas of potential conflict or consensus among competing priorities, providing an analytical foundation for land-use allocation and, when applicable, scenario development. Two of these studios have also relied on other planning approaches, including Scenario Planning (AVIN 2012), incorporating more exploratory and qualitative perspectives, rather than normative ones, to prepare for uncertainties such as variations in economic growth, effects of climate change, among others.

The goal of this paper is to reflect on and assess past projects, while also identifying broader pedagogical implications emerging from these implementations. By comparing implementations across different scales, durations, and technical configurations, the paper examines how variations in workflow, group structure, and data readiness influence both learning processes and design outcomes. In this sense, the paper not only compares technical implementations but also reflects on the kinds of reasoning, collaboration, and cross-scale thinking that these geodesign applications inherently foster.

2 Background and Methods

In our work at the University of Georgia (UGA), the idea of Geodesign has been embedded in several Urban Planning and Landscape Architecture Studios, as well as through short-term projects derived from collaborations with Professor Carl Steinitz and Hrishikesh Ballal (University of College, London), and the Coastal Regional Commission of Georgia (RIVERO et al. 2015, 2017, 2018, SMITH et al. 2020), and with faculty and students from the NASA Develop program Georgia node, led by the Center of Geospatial Research at UGA. These projects date back more than 10 years, with the first NASA Develop project in Miami starting in 2014 and the first Coastal Georgia Geodesign in 2015. This combined experience, across academic and non-academic projects, service-learning studios, and collaborative teaching environments allows us, ten years later, to compare and reflect on the challenges and opportunities offered by each of these approaches, as well as areas for future improvement. Frameworks applied in these projects include Steinitz and Ballal's Geodesignhub (BALLAL 2015), LUCIS (CARR & ZWICK 2007), ESRI's Geoplanner, and hybrid approaches incorporating scenario planning.

This paper briefly assesses and compares four case studies, all based on unique platforms and methods, implemented as Studios working with students and grounded in a geodesign framework. Previous comparison of geodesign studies in research and education has been presented by Gu et al. (2020) and Campagna (2022). These authors have used certain metrics as a qualitative taxonomy to compare their projects, based on context (research, education, training, strategic planning), focus (methodology, design, capacity building), tools, mode (online, in-person), duration, and type/number of participants (researchers, students, municipalities). Although this could have been an appropriate approach, given the variety of cases our group has worked on, we decided to focus only on studios to draw more useful conclusions for pedagogical purposes. In our studio projects these are indicators that we identified as more valuable for comparative purposes: scale, stage – inventory/system, stage – analysis/evaluation/suitability, stage – design, type of platform for mapping and analysis + level of expertise, group configuration, definition of stages and scope of study, collaborative approach, collective knowledge acquired/level of detail of proposals.

3 Summary of Case Studies

Georgia offers an excellent ground to explore planning scenarios for future development with multiple stakeholders, as it has areas at different stages of urban expansion and rapid growth, including, among others, counties surrounding the city of Atlanta and some counties in the Coastal region. Because of the multiple actors and interest groups competing for land in the state, it provides the perfect ground to experiment with various geodesign approaches that help students better understand these complex urban problems, including their opportunities and potential conflicts derived from these competing interests. One of the Geodesign frameworks implemented in these projects, LUCIS (CARR & ZWICK 2007) was also born from similar experiences in Florida, as consequence of urban development pressures in regions such as the Orlando Metropolitan area, South Florida, and even rural areas in North Florida, where some of the ecology of the groundwater and karst topography was still in process of being understood.

These are the four case studies (three of them in Georgia – Fig. 2 – and one in Iowa): A. 2018 Coastal Georgia, B. 2024 Jackson and Barrow Counties, C. 2025 Newton County and City of Porterdale, and D. 2022 City of Aimes, Iowa.

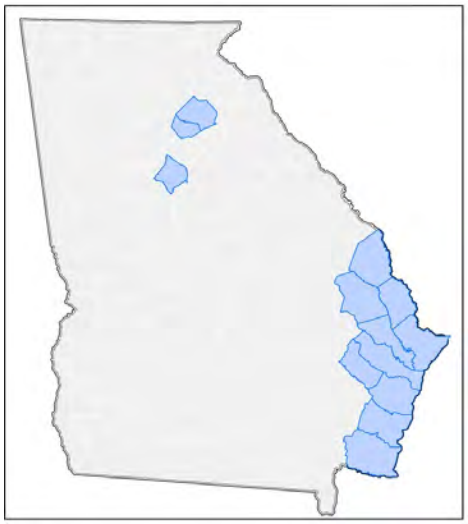

Fig. 2:
Case Studies in Georgia: A. 2018 coastal GA, B. 2024 Jackson and Barrow Counties, C. 2025 Newton County

The 2018 Coastal Georgia Geodesign project was part of a larger international initiative, the IGC International Geodesign Collaboration, described in depth in Steinitz et al. (2022). This was a macro-region (10-county) previously studied in collaboration with the Coastal Regional Commission of Georgia, as part of our first two collaborations with Steinitz and Ballal, using the Geodesignhub online system (RIVERO et al. 2015 & 2018). This Studio applied a hybrid approach, combining techniques and processes from a traditional Studio (inventory, analysis and synthesis, site design) and those from Steinitz's Geodesign (Systems Evaluation, Identification of projects and policies per system, interest groups team designs, and negotiation). The online collaborative workflow (Geodesignhub) supported rapid iteration and real-time comparison of models (representation/evaluation/change/impact/decision), enabling negotiation across interest groups and across two scales (RIVERO 2015). The ultimate scope of

this project was to propose 2035 and 2050 scenarios for early, late, and no adopters of a series of sustainable projects and policies for 10 systems, with a final negotiated proposal based on industry, conservation, and developer groups of stakeholders (Fig. 3).

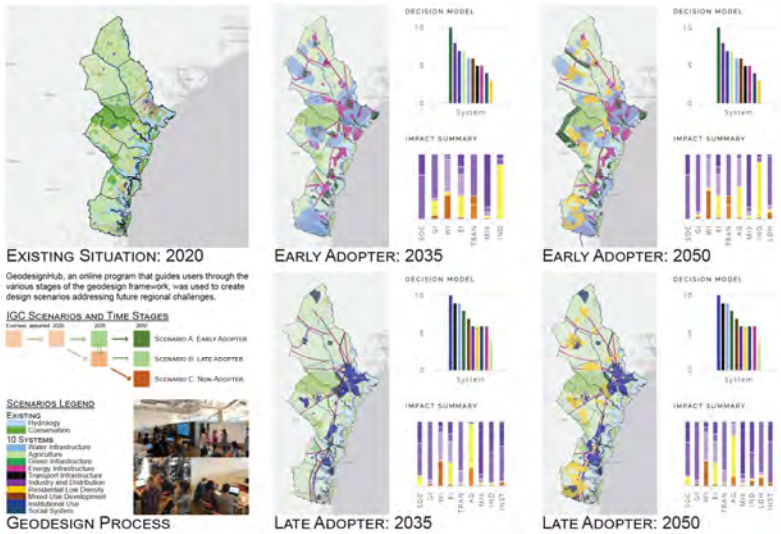

Fig. 3: Standard Scenarios developed in the 2018 Coastal Georgia Studio, using standard scenarios as defined by the International Geodesign Collaboration (IGC) leading group

Fig. 4: 2022 Ames, Iowa Studio. Impact and Scenarios Developed with Geoplanner.

The 2022 Ames, Iowa project was a partnership with the University of Iowa, and it has also been reported in two publications (MOURA et al. 2023, RIVERO & POPLIN 2025). This project had two components: 1. The application of another digital online tool (ESRI's Geoplanner) instead of Geodesignhub, for the representation, evaluation, and digital design of alternative scenarios, and 2. The application of two merged frameworks: geodesign and scenario planning. A final stage in this project is the negotiation, using the five categories or dimensions to evaluate changes, as suggested by Avin (2007) in the context of external contextual environments: society, technology, environment, politics, and economics (STEPE). Figure 4 shows the final stage of that negotiation.

The 2024 Jackson and Barrow County project represents a novel adaptation of the LUCIS geodesign framework, previously described, which had been applied by the other projects in Miami and Atlanta as part of the NASA Develop program. The LUCIS model approaches evaluation as a set of suitability models that already incorporate the criteria and weights established by 3 stakeholder groups. Suitability of these three groups is later converted into a 3-digit stakeholder preference that is overlayed to identify areas of potential conflicts, when areas in conflict are of highest priority for all 3 interest groups. In this project, a set of 6 suitability maps, one for each land use in the area, was developed as part of the evaluation and then combined into a single composite map that represents each land use. Three regional design strategy plans were proposed, derived from the evaluation of 6 systems/land uses (see Fig. 5). The regional designs created reflect three priorities rural preservation, corridor development, and overall growth.

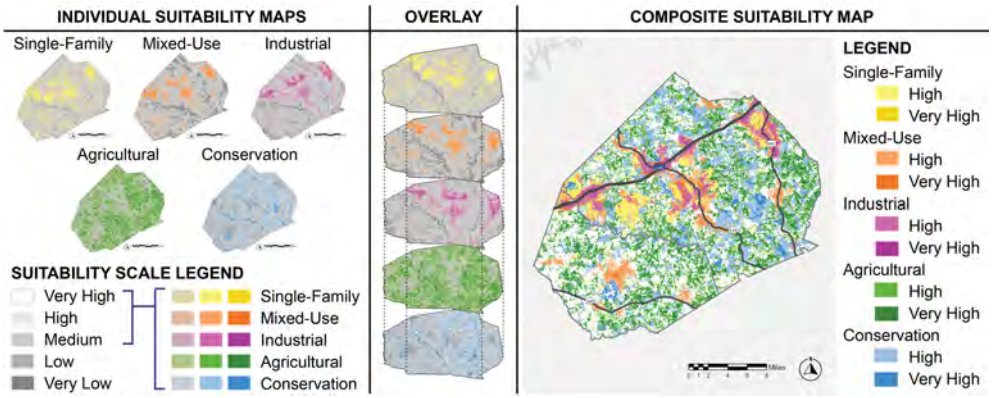

Fig. 5: Suitability Models, overlaid composite, and final suitability for Jackson and Barrow Counties, Georgia

The 2025 Newton County and Porterdale Studio is the final variation, fully implemented with ArcGIS software (with some basic uses of ArcGIS Online), but based on the same ideas of Steinitz' original geodesign framework. The 2025 Studio extended our ongoing experimentation with multiscale geodesign as a teaching model. Steinitz's three iterations framed the semester (STEINITZ 2012), complemented by scenario-planning concepts (AVIN 2012, GOODSPEED 2020, Zapata 2012) and prior inter-university collaboration work implemented in Iowa (MOURA et al. 2023, RIVERO & POPLIN 2026). The intent was to train students to reason across scales – from region to city cluster to municipality to a single site – while exploring how regional forces shape small-town futures and how local aspirations may influence broader networks. In Geodesign, defining the problem starts with identifying key strengths and threats to a region, in this case, a small cluster of cities, with strong rural and historic character, one of them (Porterdale) being a historic mill town, still "untouched" by the urban growth pressures of Atlanta, one of the most important cities of the Southeast. Newton County, Georgia, offered a pedagogically rich context. Covington and Oxford are experiencing population growth, recreation-based tourism expansion, and industrial investment, while Porterdale – a historic mill town – has experienced a one-third population decline in the last decade (Fig. 6). This juxtaposition created an ideal setting to explore resilience, heritage preservation, and cross-jurisdictional coordination in a region that is in close proximity with rapidly growing Atlanta.

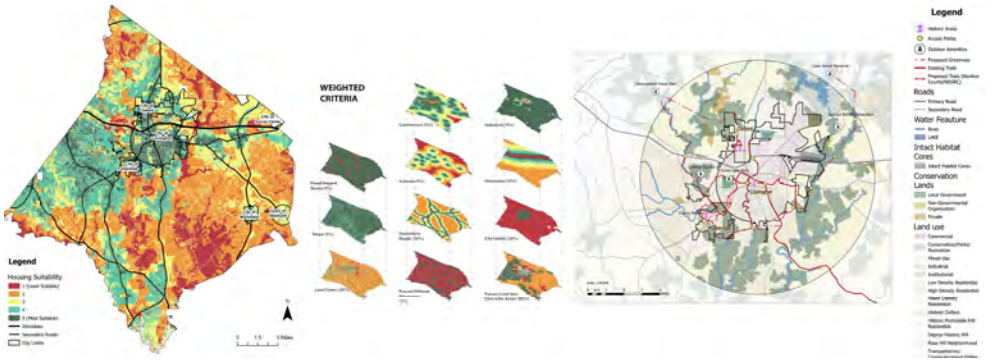

Fig. 6: Housing Suitability Model for Newton County, and local 3-City (Porterdale, Covington, and Oxford) Recreational Plan, both derived from multiscale criteria and objectives for the region

4 Comparative Review

Studios were compared using the taxonomy described in the methods section, including scope, year, scale/region size, students (number and composition), stakeholders, duration, technology/methods, systems/type of platform for mapping and analysis, and outputs. We thought about incorporating differences among geodesign stages and associated assignments (inventory/system, stage, analysis/evaluation/suitability, and stage design), but we found it challenging to compare them and included this in the final reflection and discussion.

Table 1: Comparative matrix of all four studios

Studio Project	**2018 Coastal Georgia**	**2022 City of Aimes, Iowa**	**2024 Jackson and Barrow Counties**	**2025 Newton City and the City of Porterdale**
Scope	Macro-region with multiple years and trend-based and sustainability-based Scenarios	ESRI Geoplanner based with 2 Scenarios and Negotiation	LUCIS-based Geodesign Approach	Multiscale hybrid following Steinitz and GIS methods
Scale/ region size	10-county Coastal Region of Georgia (Bryan, Bulloch, Camden, Chatham, Effingham, Glynn, Liberty, Long, McIntosh, and Screven County)	City-scale (Ames, Iowa)	2-county scale (Jackson and Barrow Counties, GA)	1-county scale with multi-municipal focus (Newton County, GA: Covington-Oxford-Porterdale; emphasis on Porterdale mill district)

Studio Project	2018 Coastal Georgia	2022 City of Aimes, Iowa	2024 Jackson and Barrow Counties	2025 Newton City and the City of Porterdale
Students	~5 MLA and MUPD UGA graduate students among ~25 total participants	Iowa Undergraduate students and Georgia Graduate students	Small group of Urban Planning Graduate Students (8 students)	Large groups of Planning Graduate Students (13)
Stakeholders	Coastal Regional Commission of Georgia, Marine Extension and Carl Vinson Institute (UGA)	City of Aimes Sustainability representatives, University of Iowa Sustainability, and Iowa State University representatives	Northeast Regional Commission of Georgia Planning Department, and U.S. Forestry	Local developer (owner of a historic mill and a few other properties), jurisdiction government representatives, and local business concerns
Duration	½ semester with the rest of the semester following a more traditional Studio sequence	One semester	One semester	One semester
Technology/ Methods	GeodesignHub, ArcGIS software, and adobe graphic tools for designs	ESRI Geoplanner and ArcGIS online hub for reporting	LUCIS Model/ ArcGIS Pro	ArcGIS Pro
Systems	10 systems (green infrastructure, housing, transportation, and others)	3 sustainability systems (green infrastructure, energy, and transportation)	6 land use/systems combined with 3 types of scenarios: rural preservation, corridor development, and overall growth	3 aggregated scales (regional, county, 3-cities), with focus on housing, recreation and greenways/trails systems, and community-based
Outcomes	One single negotiated geodesign design, from 4 original interest/ stakeholders groups (industrial/conservation/development	One single negotiated design from two groups, both proposing alternative solutions in transportation, green infrastructure, and energy, for the city	One single negotiated design with focus areas for transportation (regional light rail proposal), wildlife corridor, and housing proposals	3 multiscale and multifocus proposals, with one regional housing proposal, one 3-city region greenways and trail proposal, and one local city-wide and site-specific (historic mill) proposal
Delivery	Poster	ESRI Story Map	Poster and Report	Poster and Report

5 Reflection

From a pedagogical perspective, guiding values, knowledge, and skills are the foundation of any curriculum, and Studios represent a particular environment where these are acquired through experiential learning. Our results indicate that each Studio has been effective in contributing to the original student learning objectives, as students have developed an in-depth, ***collaborative knowledge*** of the area, addressing all scales (from region to city and vice versa), but also developing a capacity to assess this knowledge as a function of stakeholder ***values and priorities***, as well as sounded criteria for evaluation. In the process of doing this, students put in practice many practical ***skills and tools*** for collecting and analysing data, defining objectives and measurable criteria and indicators, evaluating, and later designing and sketching. Overall, the collective knowledge generated from the sequential geodesign approach (which starts with defining the scope of the project, the definition of the design/research problem, and the definition and discussion of boundaries) proves to be successful at the end, although challenging for some students during the preliminary stages, particularly those interested in following more structured instructions and less open to exploratory learning experiences. Rather than producing isolated design schemes, each case functioned as iterative learning environments in which analytical reasoning, negotiation, and implementation were closely linked.

The projects derived from Steinitz's original geodesign framework followed the 3-sequence overall methods established in his framework: first iteration (scoping the study), second iteration (selecting methods and processes, from stakeholders' decision models to evaluation model, to representation model), and third iteration (implementing the study). The Iowa project was successful in integrating two frameworks (Steinitz and Scenario Planning), while also maintaining a collaboration with faculty and students from both universities (Iowa State and Georgia University). The two groups combined their knowledge and experiences; the Iowa group contributed their knowledge of the city, while the Georgia group contributed a better understanding of methods and geodesign platforms. The Georgia project adopted several ESRI platforms (Geoplanner and Hub) for their analysis, sketching, and negotiating their design proposals, and presenting their results.

A geodesign workshop, which in many projects is the ultimate phase, should require very minimal training. However, to teach a full-semester of geodesign-based studio requires that students (or at least a subset of them) learn how to conduct a successful evaluation, with weights and criteria that are also to be defined by them. Our experience in other non-studio projects depended on substantial preparatory work, including assembling a planning team, preparing assessment mapping and criteria, testing and monitoring technology, and balancing participant expertise, suggesting that prepared data and instructional scaffolding are prerequisites for equitable participation (RIVERO et al. 2015).

Across the cases examined, a recurring tendency emerged for student work to achieve greater analytical depth and design specificity at the city or single-county scale than at broader regional extents. Large regional studies proved effective for early systems thinking and problem framing, particularly during the first iteration of the Steinitz framework but more focused geographic scopes enabled clearer translation of analysis into actionable planning and design proposals. Even in the most recent studio, which was intentionally structured as a multiscale exercise, student teams ultimately concentrated their efforts at intermediate or localized scales to advance implementable proposals. These observations suggest that regional-scale

analysis function most effectively as a contextual foundation, while focused scales better support decision-making and design development.

Two challenges have emerged from our experience with physical design planning studios in Georgia, particularly with large-scale planning studios (the last studio in a series of three, moving from local to regional scale). One is the limited design and graphic representation skills when students come from very diverse backgrounds (political science, real estate, engineering, etc.). This first limitation is outside the scope of this paper. The second is the level of comfort or fluency in applying their technical skills in studio projects, particularly GIS and other platforms and analytical workflows. The way to overcome this is to pair students with a greater interest and knowledge in advanced GIS-based analysis to execute the models and evaluation matrices, which are products of broader discussions among team members. The evaluation and analysis/synthesis phase tends to be difficult for students without a design background (and even with that) because many tend to focus on broader policies or rely on existing ones rather than think creatively and propose new ones. In those cases, using suitability as the primary evaluation method may not be the best approach. But these students can also benefit from learning to define evaluation indicators, develop evaluation matrices, and assess stakeholder values beyond a very conceptual, generic framework. Software-wise, ArcGIS proved to still be the best way to perform evaluation. Online tools to perform this (e. g., ESRI Geoplanner) were not well developed for all systems (except for green infrastructure), and therefore are limited in the use for non-experienced GIS users.

Variation in cohort size across the cases also shaped group configuration and collaborative dynamics. The smaller 2024 cohort (approximately eight students) limited the number of teams but supported deeper shared understanding across analytical and design tasks within each group. By contrast, the larger cohort (approximately thirteen students) enabled the formation of additional teams and a more explicit division of scales and stakeholder perspectives, expanding analytical coverage but also introducing greater coordination demands. Group configuration thus emerges as an intentional pedagogical design variable, closely tied to cohort size, study scale, duration, and analytical complexity.

Acknowledgements

Each of these projects was made possible by the participation of many students, collaborators, guest speakers, and other participants. The 2018 Coastal Geodesign Studio was possible thanks to the collaboration of two other faculty members, Alison Smith and Robert Vick, along with Carl Steinitz, Hrishikesh Ballal, the Coastal Regional Commission of Georgia, Carl Vinson Institute, and Marine Extension. The 2022 Aimes, Iowa Studio was made possible thanks to funding from the University of Georgia Graduate School and the College of Design at Iowa State University, and guest speakers Carl Steinitz and Uri Avin. The last two Studios (Jackson, Barrow, and Newton County) were conducted in collaboration with staff from the Northeast Georgia Regional Commission, Professor Jack Crowley, and business partners in the development of Porterdale, Newton County.

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From Narrative Evidence to Structured Insights: Leveraging the LLM to Scrutinize 210 Landscape Performance Case Study Briefs

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Abstract: Landscape performance assessment is essential for evidence-based design, yet existing narrative evidence remains fragmented and difficult to synthesize. This study develops a Large Language Model (LLM)-assisted workflow to systematically examine 1,607 assessed benefits from 210 Case Study Briefs published by the Landscape Architecture Foundation (LAF). A binary framework was developed to appraise assessment quality and implemented using Gemini 2.5 Flash, demonstrating high consistency with expert validation. Results reveal a persistent hierarchy in assessment quality, with environmental benefits significantly outperforming social benefits. Longitudinal analysis indicates marked improvement in assessment quality between 2010 and 2020, followed by a quality plateau during the 2021-2025 period. This stagnation is associated with enduring limitations in empirical data collection, particularly the lack of primary data and direct measurements. The findings suggest that landscape performance assessment has reached the limits of report standardization and that future progress will require a shift toward technological integration, emphasizing advanced sensing technologies and validated measurement tools to strengthen empirical robustness.

Keywords: Landscape performance, quality appraisal, evidence-based design, LLMs processing

1 Introduction

Emerging studies in landscape architecture increasingly prioritize evaluating design projects from an outcome's perspective, which is recognized as landscape performance (YANG 2020). Landscape performance emphasizes assessing the broader environmental, economic, and social impacts of design interventions instead of merely quantifying physical outputs (CANFIELD et al. 2018, LIU et al. 2024). For example, rather than simply quantifying green coverage on a university campus, a research team in China assessed its social benefits by examining how exposure to green environments facilitates various types of physical activity (MAO et al. 2025). Moreover, landscape performance aligns closely with practical projects because it directly reflects the processes and intentions of landscape design (CHEN, S. et al. 2024). Landscape architecture projects involve addressing complex land-use conditions, while also responding to the diverse aspirations and concerns of multiple stakeholders (CAI et al. 2022, PARVIN et al. 2022). As a result, they often embody explicit or implicit goals to achieve environmental, social, and economic benefits (HOSSEINPOUR et al. 2022, KING et al. 2022, SALLIOU et al. 2025). In these cases, landscape performance can provide more robust scientific evidence to support practical decision-making (BARNES 2024).

The Landscape Architecture Foundation (LAF) launched the Case Study Investigation (CSI) program in 2010, which annually funds collaborative teams of faculty, students, and practitioners to assess the impacts of exemplary landscape projects (CANFIELD & YANG 2014). These teams assess each project's environmental, social, and economic benefits, along with

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assessment background, methods, sources, and limitations, and compile their findings into Case Study Briefs (SHEN et al. 2023). Following peer review, the briefs are published on the Landscape Performance Series (LPS) platform (CANFIELD et al. 2018). As of October 2025, the platform has collected 210 briefs, forming a substantial body of narrative evidence on landscape performance.

A systematic review of existing briefs is essential to translate scattered narrative evidence into structured insights. The LAF developed a guidebook that organizes assessed benefits into a hierarchical framework (CANFIELD et al. 2018). However, the manual synthesis of newly identified benefits is highly labour-intensive, particularly as new briefs are added to the LPS platform on an annual basis. Compounding this challenge, the field lacks a standardized integration workflow, leading to duplicated efforts. Consequently, the narrative evidence contained in these briefs has not been effectively consolidated, leaving documented experiences fragmented (CANFIELD & YANG 2014).

A further barrier is the absence of consensus on how to appraise the quality of existing landscape performance assessments. Quality expectations vary across disciplinary communities and stakeholder groups. For example, project managers and designers tend to emphasize the replicability of landscape performance assessment for practical purposes, whereas policymakers rely more heavily on rigorous methodologies and high-quality data to support decision-making (BARNES 2024). Without an agreed-upon appraisal framework, assessment quality cannot be consistently characterized.

These limitations further restrict systematic cross-project comparisons and impede understanding of whether landscape performance assessment quality differs across environmental, social, and economic benefit domains, as well as which contextual factors may account for observed variation. Additionally, longitudinal understanding of how assessment quality has evolved over time remains unclear. Specifically, it is uncertain whether assessment quality has improved in recent years, and if so, whether such improvements are reflected in methodological rigor, data quality, or replicability. Collectively, these gaps constrain the field's ability to reference prior work, draw robust comparisons, and accumulate generalizable evidence.

In summary, synthesizing the narrative evidence within Case Study Briefs and conducting consistent quality appraisals for reliable comparisons remain significant hurdles for future research and practical applications. Large language models (LLMs) such as Gemini and ChatGPT, with strong literacy and analysis capabilities, have the potential to address these needs more efficiently. Specifically, LLMs can extract, organize, and summarize information from complex documents while maintaining acceptable accuracy (KE et al. 2025). On this basis, LLMs can integrate domain-specific expertise, including urban planning, to interpret targeted documents and provide meaningful insights (CHEN, Y. et al. 2025, WANG et al. 2024). However, standards and procedures for applying LLMs to the appraisal of landscape performance cases have not yet been established, and their reliability remains to be validated.

To address these gaps, this study aims to:

1) Establish an LLM-assisted workflow to systematically synthesize existing and future Case Study Briefs on the LPS platform.
2) Develop a stakeholder-responsive framework for appraising the quality of landscape performance assessments and validate the reliability of the LLM-assisted appraisal.
3) Compare assessment quality across projects by environmental, social, and economic benefit domains and over time.

2 Materials and Methods

2.1 Synthesizing the Case Study Briefs

As illustrated in Figure 1, a systematic workflow was established to synthesize 210 Case Study Briefs. All assessed benefits from existing projects were categorized according to the LAF guidebook into environmental, social, and economic types, along with their nested subtypes (CANFIELD et al. 2018). First, project-level contextual information was extracted from summary table provided by the LPS platform, including "Project Name," "Project Type," "Location," "Size," "Budget," "Project Completion Date," "Year Evaluated," "Assessed Benefits," etc. However, detailed assessment procedures for specific benefits are documented separately in each case's Method Document. These Method Documents were saved, verified using Python scripts, and linked to the summary table through shared fields "Project Name".

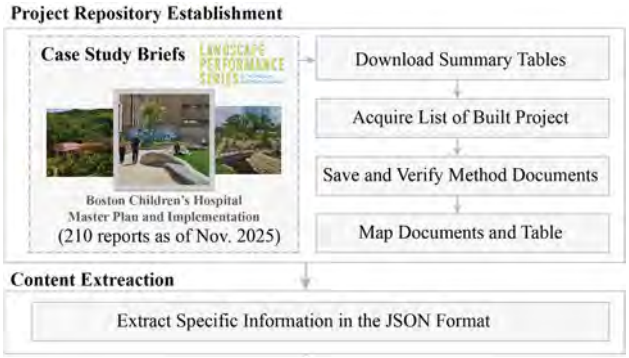

Fig. 1: Workflow for Synthesizing the Case Study Briefs

In this repository, the Method Documents were text-extracted and organized into JSON format, where each specific benefit content is treated as a primary object. Under each benefit object, the corresponding "Background," "Method," "Calculations," "Sources," and "Limitations" are nested. This process was automated using the LLM (Gemini 2.5 Flash), with finetuned prompts and a predefined JSON template (DAGDELEN et al. 2024).

2.2 Appraising the Quality of Landscape Performance Assessments

The benefits synthesized in JSON format were subsequently appraised using a binary framework based on 12 criteria across three dimensions (Table 1). These dimensions include "Methodological Rigor," "Data Quality," and "Replicability," which response to the need of different stakeholders. The automated appraisal was implemented using Gemini 2.5 Flash through structured prompt-based procedures (CHEN, Y. et al. 2024). It should be noted that the binary scoring method was intentionally adopted as a methodological trade-off between capturing nuanced details and managing analysis costs.

To assess the reliability of the LLM-assisted approach, an independent expert in landscape performance conducted the appraisal using the same framework and JSON-formatted dataset. To balance manual workload with accuracy, a random sample of 71 benefits was established as the benchmark for one-to-one meshing with the LLM outputs. The inter-rater consistency

was subsequently calculated using Intraclass Correlation Coefficients (ICCs) at both the total score and dimensional levels, testing the LLM's multidimensional reliability.

Table 1: Appraisal framework for the quality of landscape performance assessments

Dimension	Criterion	Description
Methodological Rigor	Is Quantitative	1: Method or Calculations include numerical measurements, counts, or models. 0: Purely qualitative or anecdotal.
	Uses Validated Tool	1: Method names standardized tool, model, or recognized database. 0: Generic or unverified tool.
	Uses Comparison	1: Method includes comparison to control, baseline, or pre-project. 0: Only project measurements, no reference.
Data Quality	Is Primary Data	1: Data collected firsthand for this project. 0: Relies entirely on secondary data.
	Is Direct Measurement	1: Measures the benefit itself. 0: Measures a proxy to infer the benefit.
	Is Sufficient Duration	1: Data collected over meaningful timeframe. 0: Snapshot or very short period.
	Is Sufficient Scope	1: Data collected across multiple locations, large sample, or representative conditions. 0: Very limited scope.
Replicability	Is Protocol Transparent	1: Clear, step-by-step procedure. 0: Vague description.
	Is Calculation Transparent	1: Calculations show formula, raw data, or steps. 0: Only final result reported.
	Are Sources Specific	1: Sources are specific and findable. 0: Sources vague or unspecified.
	Are Limitations Acknowledged	1: Contains relevant clear weaknesses. 0: Empty or irrelevant.
	Is Method Benefit Aligned	1: Method measures exactly the claimed benefit. 0: Mismatch between method and benefit.

2.3 Comparing the Assessment Quality Across Projects

Due to semantic inconsistencies of assessed benefits between the Method Documents and summary tables, directly linking appraisal results with project-level metadata is not feasible. To solve this, an automated record linkage pipeline was employed, utilizing the Ratcliff-Obershelp algorithm for textual similarity and global optimization to ensure unique one-to-one matches. (CHRISTEN 2012, KUHN 1955). The pipeline was implemented in Python via the *difflib* and *SciPy* libraries (VIRTANEN et al. 2020). Following iterative testing, a similarity threshold of 0.2 was empirically determined to retain acceptable matching results.

Subsequently, multiple linear regression models were fitted to examine the main effects of project-level contextual variables (Year Completed, Year Evaluated, and benefit type) on appraisal scores. For the Year Evaluated, post-hoc pairwise comparisons were conducted using Tukey's Honest Significant Difference (HSD) test to identify specific differences. To examine longitudinal trajectories of assessment quality, interactions between "Year Evalu-

ated" and appraisal scores were analyzed and visualized. In addition, Pearson correlation coefficients were calculated to evaluate interrelationships among the three appraisal dimensions. All statistical analyses were conducted using the R statistical environment.

3 Results

3.1 Project Repository of Case Study Briefs

This study consolidates previously scattered Case Study Briefs into a unified digital repository in JSON format. As of October 2025, the repository organizes a total of 1,607 assessed benefits within a hierarchical structure (Figure 2). The distribution of these benefits highlights a predominance of assessed environmental benefits (673 items, 41.9%), followed by social benefits (609 items, 37.9%). In contrast, economic benefits appear least frequently, comprising just 325 items (20.2%) of the total repository.

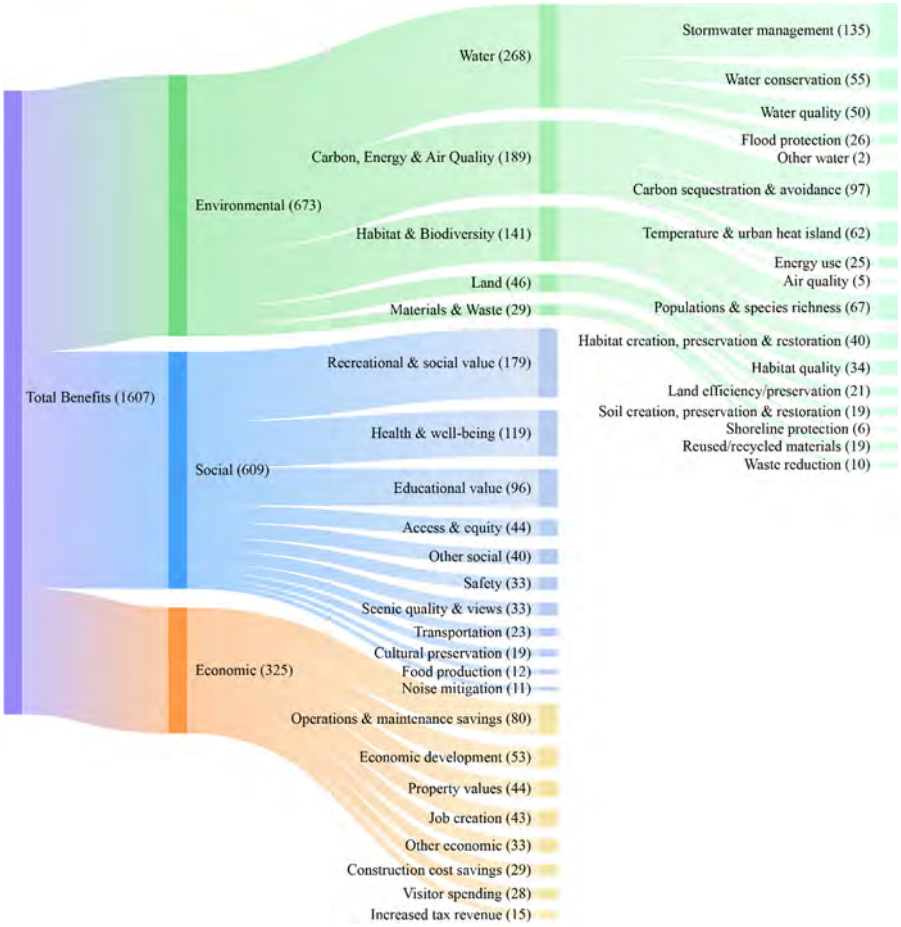

Fig. 2: Hierarchy of assessed benefits in the project repository

3.2 Quality Appraisal Results

Of the 1,607 identified benefits, 1,434 (89.23%) were validly scored and successfully linked with project-level metadata. The descriptive statistics of these valid scores indicates that quantitative reporting is nearly universal (Mean = 0.97), yet the use of validated tools (Mean = 0.28) and direct measurements (Mean = 0.24) remains limited. While metrics regarding replicability performed moderately well, such as protocol transparency (Mean = 0.70) and source specificity (Mean = 0.73), indicators for data quality were notably lower, with sufficient duration and scope both averaging only 0.30.

The validation phase demonstrates high consistency between the LLM and the human expert. The overall ICC of 0.88 confirms that LLM-assisted appraisal serves as a reliable and scalable alternative in the field of landscape performance. Specifically, Replicability achieved the highest agreement (ICC = 0.92), followed by Data Quality (ICC = 0.82), while the agreement for Methodological Rigor was moderate (ICC = 0.56).

3.3 Variabilities of the Assessment Quality Across Projects

Multiple linear regression analysis results (Table 2) reveal a rigid hierarchy in assessment quality governed by different benefit types. Assessment quality for environmental benefits achieved the highest scores ($B = 0.58$, $p < 0.01$compared to the economic baseline), while social benefits scored significantly lower ($B = -0.44$, $p < 0.01$compared to the economic baseline), revealing a structural deficit. Regression results also indicate a significant increase in appraisal scores for year evaluated compared with the 2010-2015 baseline. However, further Tukey's post-hoc Comparisons showed that this improvement did not continue into the most recent cycle. The difference between the 2016-2020 and 2021-2025 periods was not statistically significant ($p=0.273$). Interaction plots (Figure 3) further show that the trajectories of appraisal score improvements over time initially progressed in parallel across environmental, economic, and social benefits, and have visibly diverged in recent years. This divergence is reflected in the shifts across the three specific appraisal dimensions. Although Data Quality and Replicability dimensions demonstrate an overall upward trajectory across all benefit types, the assessments for economic and social benefits exhibit significant fluctuations within the Methodological Rigor dimension. In addition, the regression results show that the project completion year is positively associated with appraisal scores, likely because more recently completed projects tend to exhibit higher assessment replicability.

Table 2: Regression results for project-level contextual variables and appraisal scores

	Total Score	**Methodological Rigor**	**Data Quality**	**Replicability**
Predictors	B (SE)	B (SE)	B (SE)	B (SE)
(Intercept)	5.20 (0.38)***	1.44 (0.13)***	1.39 (0.20)***	2.37 (0.22)***
Year Evaluated				
2010–2015 (Ref.)	/	/	/	/
2016–2020	0.81 (0.15)***	0.05 (0.05)	0.14 (0.08)	0.63 (0.09)***
2021–2025	1.09 (0.21)***	0.18 (0.07)*	0.25 (0.11)*	0.66 (0.12)***
Benefit Type				
Economic (Ref.)	/	/	/	/
Environmental	0.58 (0.15)***	0.39 (0.05)***	-0.05 (0.08)	0.24 (0.08)**
Social	-0.44 (0.15)**	-0.19 (0.05)***	0.03 (0.08)	-0.28 (0.09)**

	Total Score	Methodological Rigor	Data Quality	Replicability
Year Completed				
Pre-2000 (Ref.)	/	/	/	/
2001–2005	0.30 (0.42)	-0.02 (0.15)	-0.16 (0.22)	0.49 (0.24)*
2006–2010	0.66 (0.38)	0.06 (0.13)	-0.08 (0.20)	0.69 (0.22)**
2011–2015	0.85 (0.38)*	0.18 (0.14)	-0.26 (0.20)	0.93 (0.22)***
2016–2020	1.42 (0.41)***	0.14 (0.15)	0.10 (0.22)	1.18 (0.23)***
2021–2025	1.21 (0.50)*	0.01 (0.18)	-0.34 (0.27)	1.54 (0.29)***
Significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001 Note: "Ref." indicates the reference category for categorical variables.				

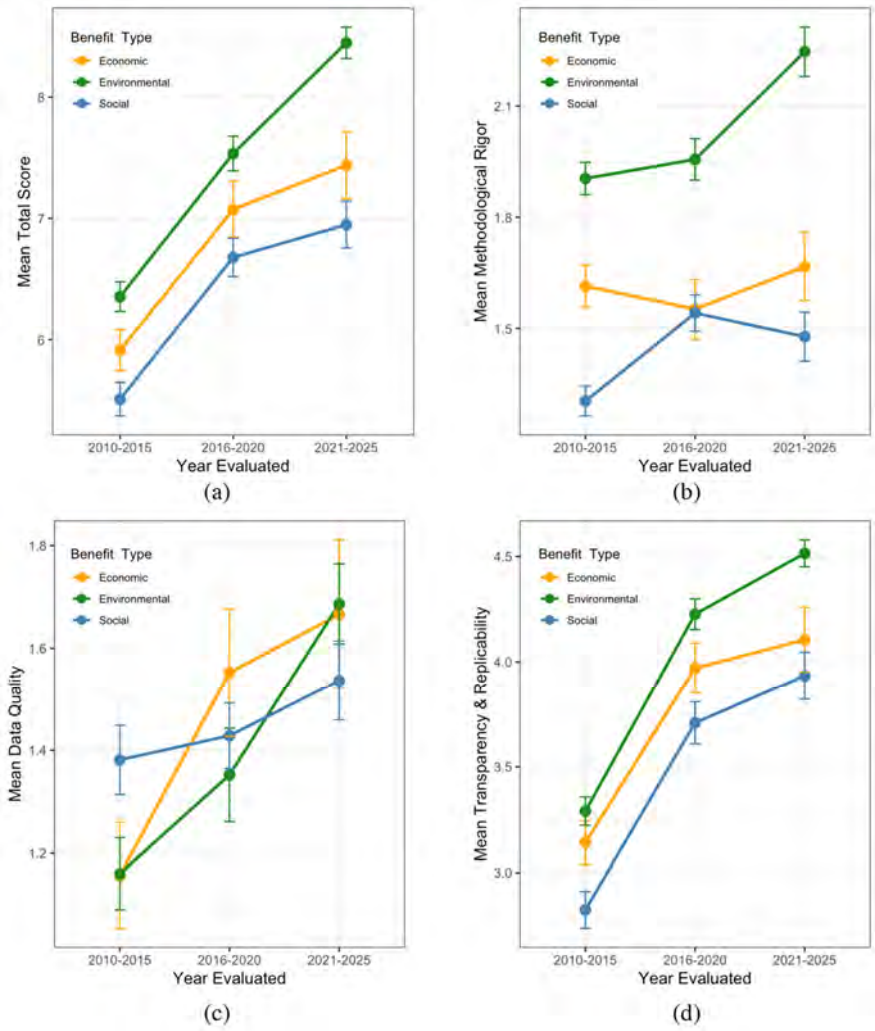

Fig. 3: Interaction plots between "Year Evaluated" and appraisal scores

Table 3 indicates generally weak to moderate positive correlations, suggesting that the three dimensions measure distinct aspects of assessment quality rather than a single unified construct. Notably, Methodological Rigor and Data Quality demonstrated the lowest correlation ($r = 0.108$), implying that the application of rigorous methods is largely independent of the quality of the data sources used. The strongest relationship was observed between Methodological Rigor and Replicability ($r = 0.351$), indicating a moderate tendency for methodologically rigorous studies to also be reported with greater replicability.

Table 3: Pearson correlation matrix of three appraisal dimensions

	Methodological Rigor	**Data Quality**	**Replicability**
Methodological Rigor	1.000		
Data Quality	0.108	1.000	
Replicability	0.351	0.191	1.000

4 Discussion

Using automated Python scripts and LLM-assisted text extraction, this study established a digital repository that continuous updates with the online Landscape Performance Series (LPS) platform. It systematically maps each project's basic information (stored as supporting metadata) to the corresponding landscape performance assessment methods, creating bidirectional retrieval opportunities. This organization better aligns with the actual needs of researchers and practitioners (PUSKÁS et al. 2021). Moreover, all data are structured in JSON format, which ensures readability for both humans and LLMs. These features enhance the data availability and methodological transparency across multiple projects.

This study also responded to different stakeholders by developing a comprehensive appraisal framework for the quality of landscape performance assessments. On this basis, this study also validated the reliability of LLM appraisal under specific constraints. By converting subjective quality judgments into binary criteria, this study minimizes the potential for LLM hallucination or ambiguity when interpreting degrees of criteria (CHEN, Y. et al. 2024). Consequently, this study achieved acceptable consistency between the LLM and human expert, demonstrating its capacity to reduce the manual effort required for large-scale appraisal. Nevertheless, further validation involving a broader range of experts is necessary to ensure the framework's generalizability across diverse contexts. In addition, it is worth noting that identical total scores do not necessarily imply identical assessment quality. We recommend examining scores across different appraisal dimensions and even at the individual criteria level to capture nuanced details. Furthermore, while binary scoring ensures reliability, we acknowledge its limitations in reflecting the full complexity of individual cases. Future research can build upon this framework to explore multi-point scoring systems or transcend rigid paradigms toward holistic appraisals, utilizing LLMs as human-like reasoners that articulate their appraisal rationale in natural language (WANG et al. 2024). Overall, the LLM-assisted framework developed in this study is reliably and flexible, allowing for fine-tuned reuse in future research.

Leveraging the LLM, this study reveals a persistent structural gap in how landscape performance is assessed in previous projects. Environmental benefits are generally assessed using more rigorous and mature protocols (e. g., i-Tree, stormwater calculators), reflecting the

greater standardization of existing environmental indicators (MEDEIROS et al. 2021). In contrast, social benefits receive the lowest average scores, largely due to the inherent difficulty of quantifying social outcomes (CHEN, S. et al. 2020). Some studies relied on self-reported questionnaires with limited sample sizes and rarely adopted validated tools. Economic benefits, although less frequently assessed, demonstrate relatively strong scores owing to the availability of standardized data and financial metrics (POLASKY et al. 2019). These findings call for evidence-based strategies, enhanced performance monitoring, refined evaluation indicators, and improved accountability in future landscape design and planning projects.

To achieve these goals, it is essential to move beyond the general comparison among the three benefit types. Considering the inevitably broad variation and idiosyncrasy inherent in individual cases, subsequent research can leverage the LLM from a micro-perspective. For instance, future studies can distil the methodological summaries and execution details of high-scoring cases into standardized templates. By translating these macro-level appraisals into micro-level guidance, concrete advice on which specific approaches could be used, we can substantially improve the overall utility and accountability of the Case Study Briefs for future practitioners.

Despite the overall upward trend, interaction analysis shows that the gap among three types of benefits is not closing, and it is widening in recent years. This is partially attributable to the fact that, while researchers are increasingly enhancing assessment replicability, the fundamental methods for measuring economic and social benefits have not evolved to match the rigorous advancements seen in environmental assessments. Furthermore, within the Data Quality dimension, the evaluation of environmental benefits initially scored the lowest but exhibited the most robust growth momentum, ultimately surpassing the other two benefit.

In addition, the lack of a statistically significant difference between the 2016-2020 and 2021-2025 periods ($p = 0.273$) suggest a potential quality plateau. It reveals a structural limit: while the form of reporting has matured, the substance of empirical measurement remains constrained by logistical and financial barriers. Specifically, the broader adoption of standardized reporting guidelines, including those developed by the Landscape Architecture Foundation (CANFIELD et al. 2018), has successfully corrected procedural deficiencies and elevated transparency scores (Mean = 0.70). As a result, researchers demonstrate increasing proficiency in documenting calculation methods and acknowledging limitations. However, the persistent low scores in Data Quality (Mean = 1.38/4) and Direct Measurement (Mean = 0.24) highlight a paradigm shift. They demonstrate that the primary bottleneck in landscape performance assessment has transitioned from a lack of reporting protocols to a fundamental deficiency in empirical data collection capacity

To resume the upward trajectory of assessment quality, the discipline must transition from a phase of report standardization to technological integration. Future improvements will rely on lowering the threshold for high-quality data collection through the widespread adoption of low-cost IoT sensors and remote sensing tools, which can replace static estimation models with dynamic, site-specific monitoring (SHEN et al. 2023). Furthermore, to address the methodological deficit in social performance, the industry must replace arbitrary questionnaires with validated psychometric instruments as standard practice. Consequently, funding bodies and research platforms should prioritize investments in long-term post-occupancy evaluation (POE) infrastructure to address the universal deficit in data duration and scope, rather than merely refining report templates (ELSAYED et al. 2023).

The low correlation between Methodological Rigor and Data Quality (r = 0.108) exposes a critical risk of "False Precision". We found that many environmental assessments achieve high rigor scores by using complex calculation models, yet these models are often fed with low-quality, secondary, or estimated data rather than on-site measurements. This creates an illusion of scientific accuracy: the calculation process looks rigorous, but the result is only an estimate. It highlights a clear distinction between reporting a complicated method and executing a high-quality measurement. For practitioners, this means one must be cautious when citing the assessment references that lack primary data verification.

In addition to time, other project-level contextual information was omitted when appraising landscape performance assessments, but it can be an important factor influencing practice choices. For instance, projects located in flood-prone regions tend to prioritize drainage-related metrics. Regional differences in data availability may also affect the depth of landscape performance assessment methods. By retaining comprehensive project metadata, the repository enables future research to examine how geographical and other contextual factors shape the rigor and diversity of landscape performance assessments.

5 Conclusion

This study demonstrates the potential of LLM-assisted workflows to support large-scale, systematic appraisal of landscape performance evidence when combined with structured data and human validation. Beyond improving synthesis efficiency, the findings reveal enduring structural limitations in current assessment practices. Despite steady improvements in transparency and replicability driven by reporting standardization, a persistent gap among three benefit types and the emergence of a post-2020 quality plateau indicate the limitations assessment methods. However, methodological refinement alone is insufficient. There exists a critical disconnection between sophisticated analytical methods and the quality of underlying empirical data. Addressing these challenges will require a disciplinary shift toward technological integration, including greater use of direct measurement, low-cost sensing technologies, and validated social indicators. Strengthening empirical data collection capacity, rather than further refining reporting formats, is essential for advancing robust, evidence-based landscape design and planning.

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The Board of Editors helps promote the quality and interests of the **Journal of Digital Landscape Architecture (JoDLA)**. This includes advising the editors on the policies of JoDLA and its future direction, and recruiting appropriate submissions. A group of experts in the areas of New Media and Landscape Architecture, mostly from the Board of Editors, but completed by additional specialists, serves as **Peer Reviewers for the Journal JoDLA**. The contributions to the journal are the result of a two-phase blind peer-review process. A total of 145 extended abstracts were initially submitted. This is the highest number ever received by the JoDLA!

Fig. 1: 145 submitted extended abstracts reviewed by 71 blind reviewers led to 122 accepted abstracts for submission of full papers for JoDLA 11-2026 – graphics provided by OpenConf

As in the last three years, the extended abstracts came from twenty-five countries. In order of numbers of submissions: 45 contributions from China, 28 entries from the United States, 12 submissions from Turkey, each six from Canada, Switzerland and Germany, five from Australia, three form Ireland. Two contributions each came from Austria, Czechia, Hungary and The Ukraine. And we have received one entry each from Brazil, Finland, India, Indonesia, Lebanon, Netherlands, New Zealand, Norway, Portugal, Singapore, Slovenia. Spain and from Thailand.

Each of the extended abstracts was reviewed by four blind reviewers. Then, one hundred twenty teams of authors from the extended abstract submission phase were invited to submit full papers for further review.

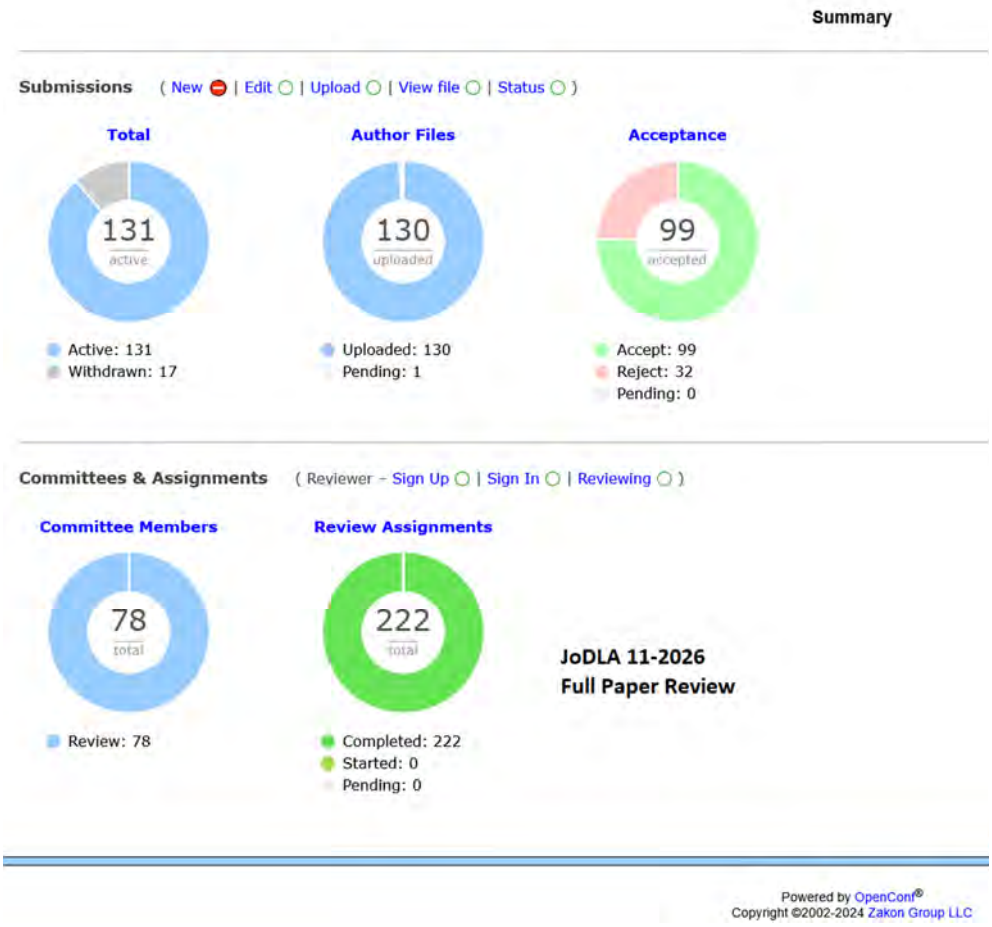

Fig. 2: 99 accepted full papers for JoDLA 11-2026 after 222 blind full paper reviews by 78 reviewers – graphics provided by OpenConf

Of those invited, 117 teams took the opportunity to continue. The anonymous peer-review process of the full papers by eighty-seven reviewers led to ninety-nine accepted contributions as peer-reviewed papers. Every paper accepted as a full paper for the journal publication was rigorously reviewed by at least two peers from the international panel of scholars.

The high standards of the reviewers assure that the papers in this eleventh issue will advance the theory and application of digital methods in landscape architecture.

The reviewers listed below spent many hours on extended abstracts and full papers. Many of them also wrote expert recommendations on how to improve the papers. **Without volunteer contribution, we could not develop this academic journal. Thank you JoDLA reviewers! And we sincerely hope that the reviewers will find time to help us in the future.**

Ackerman, Aidan – SUNY College of Environmental Science and Forestry, USA
Ahn, Susann – Vienna University of Technology, Austria
Ashari, Afshin – University of Guelph, Canada
Bartelse, Gabrielle – Wageningen University, Netherlands
Bishop, Ian – University of Melbourne, Australia
Bittner, Karl – BOKU University of Natural Resources and Life Sciences, Austria
Brown, Madeline – University of Maryland, United States
Buhmann, Erich – Atelier Bernburg Landschaftsarchitekten, Germany
Campagna, Michele – Università di Cagliari, Italy
Chamberlain, Brent – Utah State University, United States
Connolly, Peter – Victoria University of Wellington, New Zealand
Conrad, Max – Louisiana State University, United States
Danahy, John – University of Toronto, Canada
Döllner, Jürgen – Hasso-Plattner-Institut, Germany
Donaubauer, Andreas – TU München, Germany
Douglas, Craig – Harvard University GSD, United States
Dreksler, Beata – American University of Beirut, Lebanon
Ervin, Stephen – Harvard University GSD, United States
Fernberg, Phillip – Utah State University, United States
Flohr, Travis – Pennsylvania State University, United States
Formosa, Saviour – University of Malta, Malta
Fricker, Pia – Aalto University, Finland
George, Benjamin – Utah State University, Unites States
Ghabouli, Elham – Asuni, Spain
Gilbey, Eric – Vectorworks, United States
Gnädinger, Johannes – psu – Prof. Schaller UmweltConsult, Germany
Hahn, Howard – Kansas State University, United States
Harmon, Brendan – Louisiana State University, United States
Hasbrouck, H. Hope – University of Texas at Austin, United States
Hassan, Ramzi – Norwegian University of Life Sciences, Norway
Hecht, Robert – IÖR Dresden, Germany
Heins, Marcel – Anhalt University, Germany
Hurkxkens, Ilmar – ETH Zurich, Switzerland
Javet, Vincent – University of Washington, United States
Kieferle, Joachim – Hochschule RheinMain, Germany
Kim, Mintai – Virginia Tech, United States

Kim, Ikhwan – Istanbul Technical University, Turkey
Klopfer, Florian – Hochschule für Wirtschaft und Umwelt Nürtingen-Geislingen, Germany
Koch, Jennifer – Wageningen University, Netherlands
Kolbe, Thomas, H. – TU München, Germany
Lange, Eckart – Hamburg Institute for Advanced Study, Germany
Lindquist, Salvador – University of Nebraska – Lincoln, United States
Lindquist, Mark – University of Michigan, United States
Lovett, Andrew – University of East Anglia, United Kingdom
Mach, Ruediger – mach:idee Visualisierung, Germany
Mattos, Cristina – Freising-Munich, Germany
Meagher, Mark – University of Manitoba, Canada
Melsom, James – UTS University of Technology Sydney, Australia
Mertens, Elke – Hochschule Neubrandenburg, Germany
Monacella, Rosalea – Harvard University GSD, United States
Münderlein, Daniel – Kassel University, Germany
Orland, Brian – IGC, United States
Ozdil, Taner – University of Texas at Arlington, United States
Ozimek, Agnieszka – Cracow University of Technology, Poland
Palmer, James – Burlington, United States
Petschek, Peter – Landscape Architect, Switzerland
Pietsch, Matthias – Anhalt University, Germany
Polyzou, Evangelia – International Hellenic University, Greece
Rani, Medria Shekar – Institut Teknologi Bandung, Indonesia
Rekittke, Jörg – University College Dublin (UCD), Ireland
Rezvan, Mohammad – Penn State, United States
Roth, Michael – Nürtingen-Geislingen University, Germany
Schauppenlehner, Thomas – BOKU University of Natural Resources, Austria
Schlickman, Emily – University of California, Davis, United States
Schob, Maximilian – Norwegian University of Life Sciences (NMBU), Norway
Schroth, Olaf – Weihenstephan-Triesdorf University HSWT, Germany
Schwarz von Raumer, Hans-Georg, Stuttgart, Germany
Seçkin, Yasin Çağatay – Istanbul Technical University, Turkey
Sedláček, Jozef – Mendel University in Brno, Czechia
Shearer, Allan – University of Texas at Austin, United States
Stemmer, Boris – Technische Hochschule Ostwestfalen-Lippe, Germany
Stempel, Peter – Pennsylvania State University, United States
Stewart, Brendan – University of Guelph, Canada
Stokmane, Ilze – Latvia University of Life Sciences and Technologies, Latvia
Stremke, Sven – Wageningen University & Research, Netherlands
Tara, Ata – RMIT University, Australia
Thoma, Matthias – Weihenstephan-Triesdorf University HSWT, Germany
Tulloch, David – Rutgers University, United States
Tyc, Jakub – Vienna University of Technology, Austria
Vogler, Verena – McNeel Europe, Spain
Vugule, Kristine – Latvia University of Agriculture, Latvia
Walls, Wendy – University of Melbourne, Australia
White, Michael – University of New South Wales, Australia

Wissen Hayek, Ulrike – ETH Zurich, Switzerland
Zeile, Peter – Karlsruhe Institute of Technology, Germany
Zhang, Zihao – City College of New York, United States
Zwangsleitner, Florian – TU Berlin, Germany

We would like to summarize the phases of the specific review process that we apply during the review for the Journal of Digital Landscape Architecture. The sixty-nine reviewers from different areas of IT in landscape architecture, as well as all the authors, used OpenConf, an efficient online conference management system.

Prof. Joachim Kieferle from Hochschule Rhein-Main operated the management system this year, as he has done for many years. **We would like to offer Joachim Kieferle our great appreciation for his long-term commitment**.

In the first step of the blind-review process, four to five blind reviewers are asked to give an initial evaluation for each of the anonymous extended abstracts assigned to her/him and place it into one of six levels of evaluation. The average score derived from these evaluations and the written evaluations of the reviewers is the basis for accepting a paper for full paper submission.

In the second step, the blind review of the full papers, only two reviewers with in-depth knowledge of the subject matter are assigned per paper. These second reviewers are usually selected from the original group that evaluates each initial abstract, and they are asked to consider recommendations already made.

In the written suggestions, the reviewers are also asked to check for

- missing references to the literature, and
- irrelevant or mistaken assertions

The reviewers are usually able to make several suggestions for improvement. All further accepted authors are given enough time to rework their full papers according to the recommendations of the two reviewers. In this second review phase, only very few authors of full papers are asked for a complete re-submission for a later issue.

Each author receives the comments of the reviewers and additional comments by the editors for revising the full paper. When necessary, papers are returned to authors for revision until accepted by both reviewers. In some cases, additional anonymous reviewers are also asked to comment.

More than two hundred authors and co-authors of ninety-nine papers received a final confirmation letter that their contribution would be published in the eleventh issue of the Journal of Digital Landscape Architecture, 11-2026, H. Wichmann Verlag, VDE VERLAG GMBH, Berlin and Offenbach, Germany.

We would like to give special thanks to all our colleagues who serve on the Review Board and by doing so further develop the level of scientific standards of the peer-reviewed journal of this conference. We thank all of them for the extensive time spent in reviewing the abstracts and the papers**.**

The quality of the peer-reviewed papers benefits greatly from the extensive advice given in comments by the blind reviewers to the anonymous authors. We are very flattered by the academic support given by the reviewers of JoDLA.

We thank all reviewers who helped with their recommendations during the two-phase review process, and we compliment the authors for their SCIENTIFIC EXCELLENCE!

The outstanding contribution of the reviewers to this Journal may be best described by looking at the volume of recommendations given by the reviewers to the authors. The words of blind recommendations given in the comments on the papers would fill many pages of this journal! Thank you for taking the time and making the effort to share your knowledge with the authors!

The Journal of Digital Landscape Architecture Award 2026 for
HIGHEST LEVEL OF COMMITMENT IN THE REVIEW COMMITTEE
are given by the editors to

Brian Orland, University of Georgia
Travis Flohr, The Pennsylvania State University
Ulrike Wissen Hayek, ETH Zürich
Thomas H. Kolbe, TU München
Peter Zeile, Karlsruhe Institute of Technology KIT
Mark Lindquist, University of Michigan
Karl Bittner, BOKU University of Natural Resources and Life Sciences
Verena Vogler, McNeel Europe
Olaf Schroth, Weihenstephan-Triesdorf University of Applied Sciences HSWT

who each wrote more than 5,000 words in recommendations as guidance for the authors submitting full papers for review. A number of other reviewers came close to this volume of recommendations, while others kept their valuable advice to the point. They all gave helpful anonymous input to the authors as well as to the editors aiding the decision on which papers to accept for publication. All conflicting evaluations were additionally blind reviewed by one of the co-editors. Here we need to name Dr. James Palmer and Dr. Stephen Erwin. We are deeply indebted to them for their lion's share of reviewing and editing contributions, this year as in every year. An enormous number of additional recommendations for the authors are the result of this process which is a major element of the increasing quality of JoDLA.

We are also pleased to announce the following authors who received the highest possible rating by both of their blind reviewers for their full paper contribution to the 10-2025 edition to the Journal of Digital Landscape Architecture.

We are giving the
"The Journal of Digital Landscape Architecture award 2026 on SCIENTIFIC EXCELLENCE" to ten teams of authors with highest achieved score in this year.

The second highest score was achieved by 31 papers. This shows that nearly half of the papers had been rated in 2026 by reviewers as excellent papers.

The Journal of Digital Landscape Architecture award 2026 on
SCIENTIFIC EXCELLENCE is given to the ten groups of Authors with the highest scores possible given by blind reviewers:

Zhen Lei, Southeast University
Defne Sunguroglu Hensel, Southeast University and
Tong Zhang, Southeast University
for their article
"Quantifying Urban Heat Island Mitigation by Green Roofs Through Soil-Informed Hygrothermal Performance Modeling"

and to

Daniel Theidel, Anhalt University
for his article
"A Prompt-to-Image Workflow for Professional Planting Visualization: Evaluating the use of ChatGPT-4o in Landscape Architecture "

and to

Hanzhu ZUO, Southeast University
Yuanyuan LIU Southeast University and
Ying ZHOU, Southeast University
for their article
"ElderSim: A Human-Centric Multi-Agent Planning Simulator for Adaptive Optimization of Community Sports Facilities"

and to

Xuan Zhu, Southeast University
Jiaying Shi, Southeast University and
Wen You, Southeast University
for their article
"From Visual Metrics to Public Perception:Mapping Nighttime Streetscapes in Nanjing's Old City, China"

and to

Feiyu Wang, Southeast University
Jiawei Leng, Southeast University
for their article
"The Low-Altitude Data Platform:A New Paradigm for Dynamic and Interactive Digital Landscape Architecture"

and to

Nafiseh Seyedeh, University of New South Wales UNSW
Joshua Zeunert, University of New South Wales UNSW and
Ainslie Murray, University of New South Wales UNSW
for their article
"Mapping Recovery, Digital Narratives of Bushfire-Affected Roadside Landscapes in New South Wales"

and to

David Tulloch Rutgers University
for his article
“Towards a Framework for AI Ethics in LA”

and to

Agnesa Ademi, Aalto University
Pia Fricker, Aalto University
for their article
“Towards an Architecture of Shifting Boundaries:A Hydrodynamic Design Approach for Coastal Adaptation in Singapore”

and to

Hakan Erdin, Istanbul Technical University
Ebru Erbaş Gürler, Istanbul Technical University
for their article
“Integrating Photographic Place Criteria into Digital Place Making Processes:An AI-Assisted Guiding Model for Urban Landscape Revitalization”

and to

Criag Douglas, Harvard University
Stephen Guerin, Harvard University
for their article
“Visualizing the Invisible: Drawing Attention to Temporal Patterns in Spatial Dynamics”

Congratulations to all!

Jeanne Colgan, who has been on board since the very beginnings of the DLA, was once again responsible for English language proofreading. As a native English speaker, she enables the English language editorial work hosted in Germany. She worked closely with Hans G.-Rahel Eschrich, Virginia Joan Buhmann, and Noah Buhmann who checked, as well as improved, the layouts of the contributions.

We wish to thank this year’s guest editors Prof. Dr. Jörg Rekiike, for hosting the DLA in 2026 at the University College Dublin (UCD), Ireland will host this year’s DLA from May 28-29, 2026 in Dublin.

The 28th annual International Conference on Information Technology in Landscape Architecture, DLA-Con Digital Landscape Architecture DLA 2027, will be held at Anhalt University of Applied Sciences, Germany. We invite you to contribute to this conference on all aspects of technologies in landscape architecture.

We are pleased to welcome Prof. Dr. Matthias Pietsch as our next annual Chair and Prof. Daniel Theidel as our new Co-DLA Chair for 2027. Thank you for taking on this challenge. We look forward to coming back to the homebase at the Anhalt University.

Please find the early call for the next JoDLA on the following two pages. We would like to emphasize that we are continually looking for ways to publish your exciting work on the development of landscape architecture by utilizing upcoming digital opportunities. While JoDLA applauds the use of grammar-checking and AI tools to assure clarity and standard English grammar in submitted papers, generative AI poses significant risks to authors, including the accidental generation of plagiarism, fabricated citations, and the loss of an authentic, personal voice. In order to maintain professional integrity and comply with publisher policies, you must explicitly declare how AI has been used in your next contributions at the end of the manuscript, before the references.

Prof. Brent Chamberlain and Prof. Benjamin George have kindly offered to host the DLAcon at Utah State University in 2028. Anhalt University will continue to host the DLA every second year as in the past, so we look forward to continuing our international network of educators in landscape architecture and to seeing you in Dessau in 2027

The DLA conference has always been scheduled typically on the last Thursday and Friday in May, or the first Thursday and Friday in June. The personal exchange during the DLA Conference is highly valued for developing our international landscape architecture community. We hope that good international travelling conditions will be re-established soon.

The Journal Digital Landscape Architecture JoDLA will continue to be organized in Bernburg by Prof. Erich Buhmann and Jeanne Colgan. We look forward to receiving your contributions for the JoDLA 12-2027 which will then be presented in Dessau, Germany.

HOCHSCHULE ANHALT University of Applied Sciences

June 2 to 4, 2027
Dessau, Germany

DIGITAL LANDSCAPE ARCHITECTURE
DLA 2027

EARLY CALL FOR PAPERS

28th International Conference on Information Technologies in Landscape Architecture

The 28th annual International Conference on Information Technology in Landscape Architecture, DLA-Con Digital Landscape Architecture DLA 2027, will be held at **Anhalt University of Applied Sciences, Germany**.

We invite you to contribute to this conference on all aspects of technologies in landscape architecture. “Extended Abstract” should have a minimum of 1200 and maximum of 2000 words including key references. The extended abstract needs to show the progress and the uniqueness of the study in some area of Digital Landscape Architecture.

Submit the extended abstract with representative images as a pdf file online via the web-based submission system at:

www.dla-conference.com > Review System by November 1, 2026

Accepted abstracts are invited to be submitted as full papers for a second fully blind peer-review. Accepted papers will be published as fully blind peer-reviewed open access publication in **Journal of Digital Landscape Architecture 12-2027** by Wichmann, Berlin · Offenbach: www.JoDLA.info.

Main Theme and Suggested Topics:

For the **28th Digital Landscape Architecture Conference**, the Editors and the Editorial Board of the Journal of Digital Landscape Architecture cordially invite you to submit abstracts for original, unpublished presentations focusing on the conference’s main theme:

From Planning to Transformation: Digital Pathways in Landscape Architecture

The Digital Landscape Architecture (DLA) conference focuses on innovative applications, methods, and critical reflections on digital and computational technologies in landscape architecture. Contributions should therefore explicitly address the development, application, evaluation, or implications of digital tools, computational methods, or data-driven approaches in planning, design, research, or education. Submissions that merely report the routine use of established software tools (e. g. GIS or CAD) without methodological or conceptual innovation fall outside the main scope of the conference. Within this digital perspective, contributions are encouraged in the following thematic areas:

1) Social, Ethical, and Governance Aspects of Digital Technologies
2) Ecological Adaptation and Environmental Systems
3) Participatory and Collaborative Design
4) Education and Capacity Building

Journal of Digital Landscape Architecture · 12-2027

Important dates for the review process are:

Review sytem open for contributions:	September 15, 2026
Abstracts due:	**November 1, 2026**
Notification of acceptance:	December 1, 2026
Full manuscript draft due:	January 10, 2027
Revised manuscript due	February 24, 2027
DLA Conference 2027	June 2 – 4, 2027

Keynote speakers will be announced in November 2026

The conference language is English. The DLA con 2027 will be held at **Anhalt University of Applied Sciences** near the Bauhaus in Dessau**.**
We are seeking partnerships with professional associations and leading vendors.

For further information, please contact:

Prof. Dr. Matthias Pietsch, Prof. Daniel Theidel, Chairs DLA 2027, Anhalt University of Applied Sciences | matthias.pietsch@hs-anhalt.de | daniel.theidel@hs-anhalt.de

Prof. Erich Buhmann, DLA Conference Scientific Director
JoDLA Review Process: www.dla-conference.com | DLA-JoDLA@t-online.de

Profile

The Journal of Digital Landscape Architecture addresses all aspects of digital technologies, applications, information, and knowledge pertaining to landscape architecture research, education, practice and related fields. The journal publishes original papers in English that address theoretical and practical issues, innovative developments, methods, applications, findings, and case studies that are drawn primarily from work presented at the annual international DLA-Con Digital Landscape Architecture Conference. Its intent is to encourage the broad dissemination of these ideas, innovations, and practices. The Journal of Digital Landscape Architecture is listed in the international citation database Scopus. It is in the top 35% of all journals in the engineering / architecture category. JoDLA is listed in DOAJ (Directory of Open Access Journals).

The author's fee for the publication is currently 450 Euros for the standard 8 pages of print with the option of publishing extra pages at 70 Euros per additional page. With this contribution towards the publishing cost you also receive an author's copy. For the author's team, additional books at a reduced price are available. The author's publication fee includes the author's hard copy and the open access publication at www.jodla.info.

While JoDLA applauds the use of grammar-checking and AI tools to assure clarity and standard English grammar in submitted papers, generative AI poses significant risks to authors, including the accidental generation of plagiarism, fabricated citations, and the loss of an authentic, personal voice. To maintain professional integrity and comply with publisher policies, you must explicitly declare how AI has been used at the end of the manuscript before the references

More information on our series of conferences on Digital Landscape Architecture and the conference fees www.dla-conference.com

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The Journal of Digital Landscape Architecture JoDLA addresses all aspects of digital technologies, applications, information, and knowledge based in research, education, and practice pertaining to landscape architecture and related fields. The journal publishes original papers that address theoretical and practical issues, innovative developments, methods, applications, findings, and case studies that are drawn primarily from work presented at the annual international Digital Landscape Architecture conference. Its intent is to encourage the broad dissemination of these ideas, innovations, and practices. All contributions have successfully passed the double blind review process of the Journal.

This issue of the Journal of Digital Landscape Architecture, 11-2026, presents contributions from the 27th annual conference at the University College Dublin (UCD) in Ireland (May 28-29, 2026) focusing on "Cutting Edge" and covering the following 12 themes within Digital Landscape Architecture research and practice:

- AI, Machine Learning and Generative Design Tools
- AI Ethics, Frameworks and Data Analysis
- 3D Scanning, Point Clouds and BIM Modeling
- VR, AR and Immersive Visualization Technologies
- Digital Tools, Data Systems and Software
- Urban Heat, Thermal Comfort and Microclimate
- Water Management, Hydrology and Coastal Resilience
- Ecosystem Services, Biodiversity and Ecological Networks
- Geospatial Analysis, Urban Ecology and Planning
- Environmental Monitoring, Remote Sensing and Data Collection
- Participatory Design, Community Engagement and User Experience
- Landscape Architecture Education, Pedagogy and Curriculum

Editors:

Prof. Erich Buhmann, ATELIER BERNBURG (Editor-in-Chief)

Dr. Stephen Ervin, Harvard University

Prof. Dr. Pia Fricker, Aalto University, Finnland

Prof. Dr. James Palmer, State University New York

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