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Transforming Environmental Planning through Data-driven Structural Models and AI: Chances for Climate-Responsive Urban Landscapes in Riyadh, Saudi Arabia

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1 ABSTRACT

As climate change intensifies extreme heat, increases natural hazards and accelerates ecological decline, cities around the world are facing environmental pressure, creating an urgent need for climate-adaptive and data-driven landscape planning. Recent advances in earth observation and artificial intelligence (AI) now enable ecological and microclimatic processes to be analyzed at high spatial and temporal resolution, opening new pathways for evidence-basedlandscape strategies. However, despite rapid technological progress, it remains unclear how AI and data-driven methodologies can be operationalized within real-world planning to address climate-induced pressures at meaningful spatial scales. Focusing on the metropolitan context of Riyadh, Saudi Arabia, as a rapidly urbanizing city exposed to extreme climatic stress, our latest research shows that AI-enabled and data-driven landscape analytics enhance climate-adaptive planning by translating diffuse environmental signals into actionable design knowledge. Using the emerging frameworks UrbAlytics for remote-sensing-based environmental assessment, nAIture for nature-centered landscape modelling and LIM landscape information modelling®, we show how suchframeworkscouldenhance early detection of microclimatic stress, refine vegetation and land-cover diagnostics, and supportbetter informed, scenario-based design of green-infrastructure interventions. These applications support differentiated risk diagnostics, canopy-performance estimation, and microclimate-responsive spatial strategies. Taken together, these findings show that AI and data-driven models offer immediate opportunities to raise analytical precision, accelerate planning timelines and support more resilient, nature-positive and climate-adaptive urban landscapes when embedded in interdisciplinary expertise and critically interpreted.

Keywords: AI-enabled landscape analytics, Climate-adaptive landscape planning, Nature positiv , Data-driven environmental planning, Urban planning

2 INTRODUCTION

Urbanization and climate change are placing increasing stress on cities worldwide, intensifying the need for adaptive, resilient, and sustainable urban planning approaches. Over the past decade, the combined effects of rapid urban growth, rising temperatures, and environmental degradation have amplified challenges such as extreme heat, urban heat-island effects, and declining ecological performance of urban spaces (Wamsler et al., 2013). These pressures are particularly acute in fast-growing metropolitan regions, where planning decisions must respond to complex climatic dynamics under conditions of uncertainty (IPCC, 2022). As a result, conventional planning instruments increasingly struggle to cope with the speed, scale, and interconnectedness of contemporary climate-related risks (Zong et al., 2023).

In recent years, advances in remote sensing, geospatial analytics, and artificial intelligence (AI) have significantly expanded the analytical capacities available to urban and landscape planners (Weng et al., 2024). High-resolution satellite imagery, microclimatic modelling, and machine-learning techniques now enable the quantification of environmental processes at spatial and temporal resolutions that were previously unattainable (Lyu et al., 2022; Zhao et al., 2025). These developments offer new possibilities for early risk detection, scenario modelling, and evidence-based evaluation of planning interventions. However, despite the growing availability of AI-enabled tools, their integration into planning practice remains uneven and methodologically under-specified. While expectations regarding their transformative potential are high, there is still limited empirical clarity on how such tools can be systematically embedded into real-world planning workflows in a way that improves decision-making, transparency, and environmental performanceparticularly in large, climatically stressed urban contexts (Salhi et al., 2025).

To address this gap, we investigated the application of AI-supported analytical workflows for the assessment and strategic planning of urban green infrastructure using internal case studies developed by the international landscape consultancy LAND. Focusing on Riyadh, Saudi Arabia, we examined how remote sensing, vegetation indices, and data-driven environmental analyses can be combined to support scalable, consistent, and decision-ready evaluations of urban greenery in an arid metropolitan context. The analysis critically explores both the opportunities and the limitations of these approaches, with particular attention to their methodological robustness, practical applicability, and relevance for climate-adaptive landscape planning.

This paper presents a structured examination of newly developed frameworks for urban green infrastructure analysis and discusses their potential contribution to sustainable and climate-resilient landscape planning. It first outlines the methodological framework, then presents key analytical results, and finally reflects on the implications, limitations, and transferability of data-driven and AI-enabled planning approaches for practice and future research.

3 MATERIALS AND METHODS

The study proposes two methodological approaches and provides an argumentative justification for their applicability to nature-positive and climate-responsive planning in arid cities such as Riyadh. Those frameworks were developed within long-term research projects at LAND, arguing for their validity as methodological approaches advancing nature-positive and climate responsive planning, and justifying their relevance for the planning in arid urban contexts such as Riyadh. In this way, a transparent discussion of methodological choices is covered prior to empirical application, with their implementations briefly presented in the Results section.

Based on a multi-year, systematic combination of applied design practice and scientific inquiry, the LAND Research Lab leadsresearch initiatives responding to increasing demands for quantifiable, scalable, and comparable evidence in landscape and urban planning, particularly under conditions of climate stress and rapid urban transformation. With LIM landscape information modelling® (LIM), the LAND Research Lab has developed a tool based conceptually on the principles of Building Information Modelling (BIM), which has been adapted to landscape systems. Its methodological contribution lies in structuring spatial, ecological, and climatic data within an integrated information model that supports scenario building and long-term monitoring.

Drawing from this tool, analytical frameworks resulting from LAND's research follow a shared design logic: they translate heterogeneous environmental, spatial, and socio-technical datasets into decision-support information that can be integrated into strategic planning processes (LAND, 2024a).

Specifically, two interrelated frameworks form the methodological basis of this study: nAIture, and UrbAlytics. While each framework addresses different analytical scales and questions, they are designed to operate as a coherent methodological ecosystem rather than isolated instruments. conceptually on the principles of BIM and adapts them to landscape systems. Its methodological contribution lies in structuring spatial, ecological, and climatic data within an integrated information model that supports scenario building and long-term monitoring. nAIture focuses on AI-assisted sustainability assessments by linking environmental indicators with machine-learning-supported pattern recognition (LAND, 2024). The tool enables the evaluation of landscape performance across ecological and climatic dimensions, supporting evidence-based prioritization in planning decisions. UrbAlytics addresses urban climate dynamics, with a particular emphasis on heat exposure and mitigation potential. It combines remote sensing, spatial analytics, and statistical modeling to identify spatial patterns of thermal stress and evaluate intervention strategies at multiple urban scales (LAND, 2023). In this paper, these tools are introduced at a conceptual and methodological level only due to confidentiality; their methodologyand analytical outputs are presented in detail in the Results section.

The selection of Riyadh as the contextual anchor for this methodological argument is motivated by three interrelated factors. First, Riyadh is characterized by extreme climatic conditions, where heat stress, water scarcity, and limited vegetation cover pose structural challenges to conventional planning approaches (Suhail et al., 2025). Second, the city's rapid spatial expansion requires scalable and transferable planning methods capable of operating across large territories and multiple governance levels (Aldegheishem, 2023). Third, the availability of high-resolution spatial and environmental data creates a favorable environment for advanced analytical and AI-supported planning tools (Wang et al., 2025). Against this background, the methodological framework proposed in this study argues that data-driven and AI-assisted landscape planning is not merely an optional enhancement but a necessary evolution of planning practice in arid megacities (Xing et al., 2024). The LAND analytical ecosystem is therefore positioned as a means to bridge the gap between strategic visions, quantitative environmental evidence, and implementable planning actions. The methodology deliberately prioritizes argumentative clarity and conceptual transparency over immediate empirical validation. While this limits the ability to draw site-specific performance conclusions at this stage, it enables a clearer assessment of methodological transferability and planning relevance.

4 RESULTS

Building on LAND's long-standing experience in landscape and urban planning (LAND, 2025a), the results presented in this chapter document the development and application of two data-driven analytical frameworks nAIture and UrbAlytics and their capacity to generate spatially explicit, operational outputs for climate-responsive planning. The section focuses on the structure, analytical components, and resulting indicators produced by these frameworks, without interpretative evaluation highlighting that detailed information can't be shared due to confidentiality and ongoing projects.

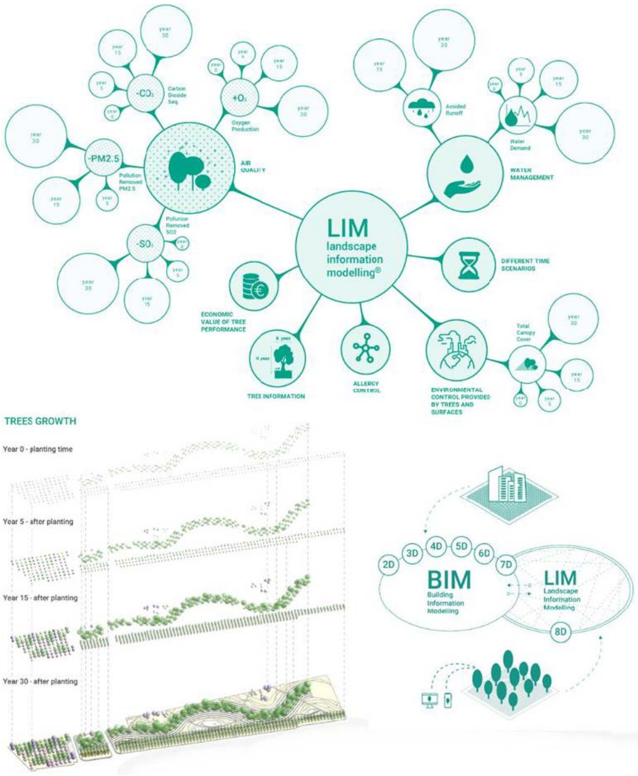

Fig. 1: Overview of LIM parameters and outputs (LAND, 2025)

4.1 NAIture

The nAIture methodology is conceived as an extension of LAND's proprietary Landscape Information Modelling (LIM) framework, advancing it from a primarily evaluative and scenario-based system toward a predictive, AI-assisted planning methodology (LAND, 2024). While LIM provides a structured, BIM-derived data environment for quantifying landscape performance over time (LAND, 2022), nAIture introduces AI as a means to interpret complex environmental datasets, identify patterns, and support anticipatory decision-making in landscape and urban planning. The methodological premise of nAIture is that landscapes are dynamic socio-ecological systems whose performance cannot be sufficiently captured through static assessments alone. Instead, planning requires iterative feedback loops between data acquisition, modelling, simulation, and design intervention. nAIture operationalize this premise by combining multi-scale environmental data with machine learning techniques to enable adaptive and scenario-responsive landscape planning. The methodological workflow of nAIture is based on the integration of heterogeneous spatial and environmental data sources into a unified modelling environment. Core data inputs include: Satellite remote sensing data, providing continuous, large-scale coverage for indicators such as land surface temperature, vegetation indices, and surface permeability. As well as Multispectral and thermal drone imagery, enabling high-resolution, site-specific analysis of vegetation vitality, water stress, and

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microclimatic variation. In addition In situ environmental sensors, supplying temporally dense data on parameters such as air temperature, humidity, soil moisture, and radiation and contextual planning and design data derived from LIM, including land-use scenarios, planting strategies, materiality, and temporal growth assumptions (LAND, 2024a). All datasets are spatially harmonized and aligned to allow cross-scale analysis, ensuring consistency between regional remote sensing data and fine-grained local measurements. AI within nAIture is applied in a task-specific and problem-driven manner rather than as a universal solution. Machine learning models are used to process large and heterogeneous datasets to fulfil three closely interrelated analytical functions: First, AI-based classification and regression techniques are employed to extract key environmental indicators, including thermal and water stress, evapotranspiration, air-quality-related ecosystem services, and pollinator attractiveness, by integrating remote sensing data with in-situ sensor measurements. Second, through the analysis of historical and real-time datasets, machine learning algorithms identify spatial and temporal patterns in landscape performance, forming the basis for predictive modelling. This enables planners to anticipate how alternative design or management interventions may influence microclimatic conditions, water performance, and ecosystem services under different climate scenarios. Finally, the derived indicators are reintegrated into the LIM framework, where they support the simulation and comparison of alternative design and management scenarios. In this context, AI functions as a decision-support mechanism that highlights trade-offs and synergies between competing objectives, thereby strengthening evidence-based planning while preserving professional judgement., and threshold effects, thereby strengthening evidence-based decision-making.

Importantly, nAIture follows a human-in-the-loop approach: AI does not replace planning expertise but augments professional judgement by making complex interdependencies visible and comparable. Within the broader planning discourse, nAIture positions itself as a bridge between data-driven environmental analysis and design-led landscape planning (LAND, 2024a).

4.2 UrbAlytics

The UrbAlytics framework was applied to assess urban heat dynamics and the microclimatic performance of Blue and Green Infrastructure at the city scale (Mantente and Castellazzi, 2023). As an experimental sub-project of the H2020-funded project AI4Copernicus aiming to bridge Artificial Intelligence with Earth Observations, the methodology was tested using the metropolitan areas of Milan and Naples as pilot case studies (ibid., 2023).Land Surface Temperature was modeled using multispectral satellite data, enabling the derivation of Surface Urban Heat Island patterns for multiple summer seasons. These outputs were aggregated to capture both intra-annual variability and longer-term thermal trends. The resulting spatial datasets reveal consistent patterns of elevated surface temperatures associated with dense urban fabrics and impervious surface coverage. Based on the LST-derived outputs, a composite Heatwave Potential Risk Index was generated. This index integrates three analytical dimensions: heat intensity, population exposure and spatial vulnerability related to urban morphology. The resulting maps provide a relative representation of heat-related risk across the urban fabric. To quantify vegetation-related cooling effects, tree-cover density and land-cover data were classified into 20 categories of Blue and Green Infrastructure. For each category, a Microclimatic Performance Index was calculated based on biophysical parameters, including shading capacity, evapotranspiration potential and surface reflectance. This allowed for a comparative assessment of different vegetation typologies and their contribution to urban cooling.

An additional analytical layer focused on Park Cool Island effects. Green spaceswere evaluated based on size, spatial configuration and structural characteristics. Their cooling performance was assessed by intersecting park extents with multi-year summer averages of Surface Urban Heat Island values (2018-2022). The analysis identified areas that consistently exhibit lower surface temperatures relative to their surroundings. The result of the UrbAlytics workflow (as seen in figure 2) is the development of a scalable, automated analytical pipeline designed to support climate adaptation planning across different urban contexts. A decision-support module is currently being developed to link spatial heat-risk patterns with a database of Nature-Based Solutions. This module enables the context-specific selection of adaptation measures based on spatial characteristics and environmental performance indicators.

The automated processing chain and the reliance on transferable Earth observation data allow for application beyond the initial case studies, supporting comparative analyses and evidence-based decision-making at the city scale (LAND, 2023).

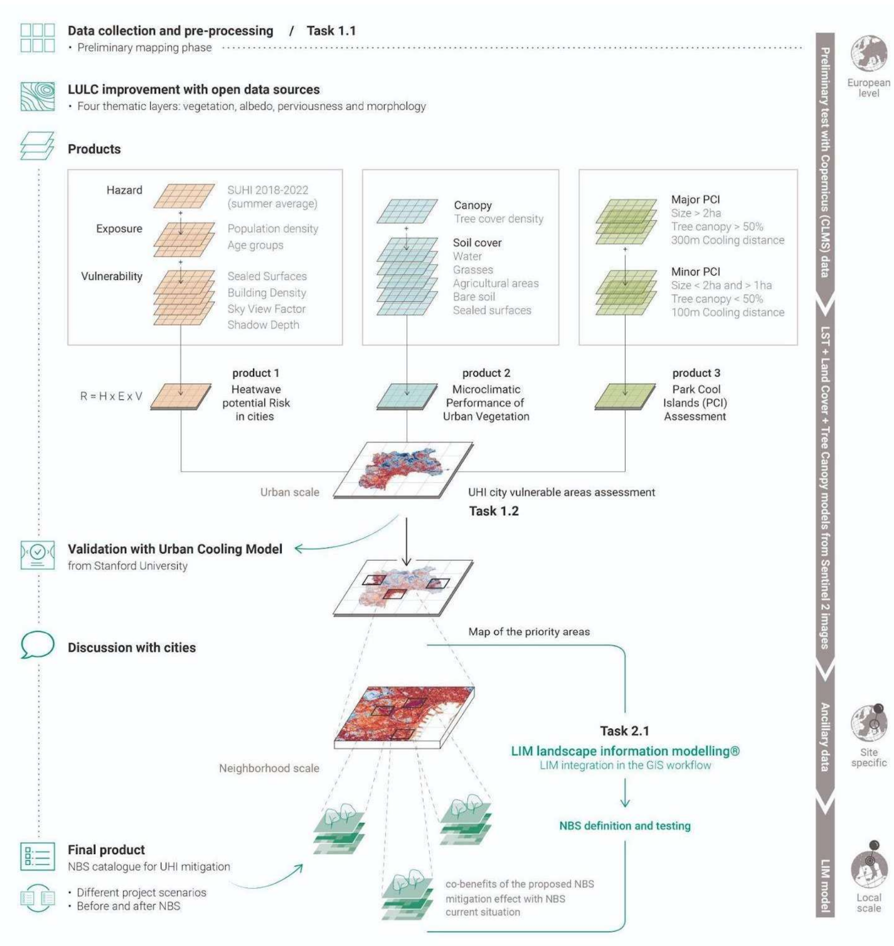

Fig. 2: Al4C Methodology Overview UrbAlytics (Mantente and Castellazzi, 2023)

5 CONTEXTUAL JUSTIFICATION: RIYADH AS A LABORATORY FOR DATA-DRIVEN ENVIRONMENTAL PLANNING

Landscapes shaped by extreme climatic conditions provide a critical testing ground for the advancement of contemporary landscape and urban planning methodologies. In such environments, the limits of conventional design-led approaches become particularly evident, while the need for anticipatory, evidence-based decision-making increases (Kenny, 2020). Arid metropolitan regions, characterized by persistent heat stress, limited water availability, and rapid spatial transformation, therefore offer a compelling context in which to examine the relevance of data-driven and AI-supported planning frameworks (Eshraghi et al., 2024).In this regard, Riyadh constitutes a particularly instructive planning context. As stated above, the city is undergoing accelerated urban growth while simultaneously facing severe climatic pressures that demand early-stage environmental assessment and long-term performance-oriented planning (Alajizah et al., 2024). These conditions challenge established planning routines, which often rely on descriptive analysis and qualitative judgement, and instead require methods capable of integrating large-scale environmental data, modelling spatial dynamics, and comparing alternative scenarios within compressed decision-making timelines (Drescher and Skoyles, 2024).

At a broader scale, Saudi Arabia is currently experiencing a fundamental shift in its planning paradigm, driven by the need to reconcile rapid development with environmental resilience and public well-being. This transition can be interpreted as comparable in ambition and societal relevance to the European Volkspark movement of the early twentieth century, which emerged in response to industrialization and deteriorating urban environmental conditions (Kipar et al., 2025). Within this context, initiatives such as the Green Riyadh program, anchored within the broader framework of Saudi Vision 2030, exemplify a state-led commitment to embedding large-scale green infrastructure, climate adaptation, and public health objectives into contemporary urban development, thereby operationalizing this paradigm shift at the metropolitan scale (RCRC, 2019). In both contexts, strategic investment in public open space reframes landscape infrastructure as a collective response to systemic pressures, positioning green and blue spaces as essential components of environmental justice, public health, and social cohesion rather than as purely recreational amenities.

Within this transformation, Riyadh functions as a laboratory for exploring how data-driven and AI-supported planning tools can operate not merely as supplementary analytical aids but as structuring elements of the planning process itself. Persistent heat stress, limited water availability and rapid spatial expansion generate environmental dynamics that are highly heterogeneous yet are commonly addressed through planning routines that rely on descriptive analysis, expert judgement and static design assumptions. Under such conditions, qualitative assessments and generalized spatial categories are insufficient to capture the magnitude, distribution and interaction of climatic stressors across the urban fabric.

The environmental processes are characterized by complex relationships between land cover, surface materials, urban morphology, vegetation structure and atmospheric conditions. These interactions operate at spatial and temporal resolutions that exceed the analytical capacity of conventional planning tools. As a result, critical factors such as localized heat exposure, differential cooling effects of green infrastructure typologies, or cumulative impacts of incremental urban growth remain poorly represented in decision-making processes. At the same time, rapid urban transformation places planning authorities under increasing pressure to evaluate alternative development pathways within short timeframes and across large spatial extents. This combination of scale, complexity and time constraint necessitates methods capable of systematically integrating heterogeneous environmental datasets, modelling spatial dynamics and enabling comparative scenario analysis. Data-driven and AI-supported approaches address these requirements by facilitating the automated processing of large-scale Earth observation data, the generation of spatially explicit indicators and the consistent evaluation of planning alternatives. Rather than replacing design-based planning, such methods provide an analytical foundation that allows environmental performance to be quantified, compared and monitored over time.

The advantages of this planning approach become evident when examining recent large-scale developments involving LAND in Riyadh, such as the Concept Masterplan forEXPO 2030(LAND, 2025) and the realization of Al Urubah Park (LAND, 2023b). Both projects are characterized by extensive spatial scope, ambitious environmental targets, and stringent time constraints, creating conditions in which conventional iterative design processes reach their practical limits.In the case of the project site covering more than 400 km² according to internal documentation, the scale and urgency of planning required a consistently digital workflow. Parametric modelling and AI-assisted analyses were embedded across concept development, spatial assessment, and visualization (LAND, 2025).

A comparable logic underpins the planning of Al Urubah Park, a major public open-space project in an arid urban environment. Here, the central challenge lies in providing microclimatic comfort under conditions of extreme heat and water scarcity. To address this, the design process relied on remote sensing, satellite imagery, and AI-based land-cover classification to generate detailed, spatially explicit information on vegetation distribution, canopy density, and surface characteristics (LAND, 2024a). These datasets were combined with performance-oriented models to estimate shading effects, evapotranspiration potential, and thermal behavior, allowing planting concepts, irrigation strategies, and spatial configurations to be informed by quantifiable environmental indicators rather than solely by conventional design assumptions (LAND, 2025).

Taken together, these examples illustrate how AI and data supported analytical frameworks enable earlier, more precise, and more scalable assessment of environmental conditions in demanding planning contexts. They demonstrate that those methods can enhance the capacity of planning processes to respond to climatic stress, provided that their outputs are interpreted within an interdisciplinary framework and combined with ecological expertise and contextual knowledge. Overalla broader shift in contemporary planning practice is required: from predominantly descriptive approaches toward methodologies that integrate environmental data, spatial modelling, and simulation to support anticipatory and evidence-based decision-making. Within this transition, the data-driven frameworks presented in this studyare positioned not as universal solutions, but as adaptable methodological propositions capable of supporting climate-responsive landscape planning in arid metropolitan regions.

6 DISCUSSION

This study examines how data-driven and AI-supported analytical frameworks can be systematically operationalized within climate-adaptive landscape planning, using the metropolitan region of Riyadh as a representative case of an arid city undergoing rapid spatial transformation.The results demonstrate that AI-enabled workflows such as UrbAlytics, nAIture, and LIM landscape information modelling® can substantially enhance the analytical depth, spatial resolution, and scalability of environmental assessments. Rather than functioning as isolated technological add-ons, these tools operate most effectively when embedded within an integrated planning logic that links environmental data, spatial modelling, and design decision-making. A central contribution of this study is the demonstration that climate-sensitive, data-driven planning tools can be developed as transferable methodological frameworks rather than as context-specific prototypes. The results show that AI-supported analytics enable the systematic integration of climatic and ecological sensitivity into planning workflows at multiple spatial scales, using globally available environmental data. While applicable across diverse urban contexts, these tools are particularly effective in arid metropolitan regions, where pronounced environmental heterogeneity and extreme climatic stress require spatially explicit, performance-oriented analysis to support robust planning and design decisions.

The results show that the integration of Earth observation data, vegetation indices, and machine-learning-based classification enables a more differentiated understanding of land cover, canopy performance, and microclimatic stress patterns. This finding aligns with recent literature highlighting the need for quantitative, spatially explicit diagnostics to support climate-responsive planning under conditions of uncertainty and complexity (Weng et al., 2024; Drescher and Skoyles, 2024). In the context of Riyadh, where thermal exposure and cooling potential vary sharply across short distances, such analytical precision is not merely advantageous but essential. This represents a qualitative shift from descriptive assessments toward performance-oriented evaluation, supporting earlier and more informed decision-making in the planning process. Another key insight emerging from this study concerns the scalability of data-driven planning approaches. Riyadh's rapid spatial expansion and the scale of its development initiatives place significant pressure on planning authorities to evaluate alternative scenarios across large territories and within compressed timeframes. The findings indicate that those workflows are particularly well suited to these conditions, as they enable automated processing of large datasets, consistent application of analytical criteria, and comparative evaluation of multiple planning scenarios. Importantly, the study does not suggest that AI replaces design expertise. Instead, the results underscore its role as an enabling infrastructure that allows environmental performance to be quantified, compared, and monitored over time. The discussion further highlights Riyadh's relevance as a laboratory for methodological innovation in climate-adaptive landscape planning. At a broader scale, the findings can be situated within Saudi Arabia's ongoing shift in planning paradigms, exemplified by large-scale initiatives such as the Green Riyadh program under Saudi Vision 2030 (RCRC, 2019). Comparable in ambition to historical European movements that repositioned public open space as a response to systemic environmental pressures, these initiatives frame landscape infrastructure as a central component of public health, environmental resilience, and social well-being (Kipar et al., 2025). Within this transformation, the tools examined in this study illustrate how those methodologies can contribute to operationalizing strategic goals by linking policy ambitions with quantifiable environmental evidence. However, the study also highlights important limitations. AI-supported planning depends critically on data quality, model assumptions, and interpretive expertise. Spectral uncertainty, transferability of models across contexts, and the risk of oversimplifying ecological processes remain significant challenges. Moreover, issues related to data governance, transparency, and accountability become increasingly salient as AI-based systems are embedded in planning practice. Addressing these issues is essential for ensuring the robustness and trustworthiness of AI-assisted planning systems, particularly in the context of smart city infrastructures (Weng et al., 2024). This requires interdisciplinary collaboration and critical oversight, reinforcing the argument that these tools should augment not replace ecological knowledge and design judgement. Taken together, the findings position data-driven and AI-supported landscape planning as a necessary methodological rather than a discretionary technological enhancement. While the study deliberately prioritizes conceptual clarity and methodological positioning over exhaustive empirical validation, it provides a structured framework for integrating AI-supported analytics into real-world planning workflows. Future research should focus on longitudinal evaluation of implemented interventions,

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comparative studies across different climatic regions, and deeper investigation into governance mechanisms that ensure ethical and transparent use of data-driven tools and AI in planning.

Overall, this study contributes to the growing body of research that frames climate-adaptive planning as an interdisciplinary, data-informed process. By demonstrating how AI-enabled tools can translate complex environmental data into decision-relevant knowledge, it underscores their potential to support more resilient, nature-positive urban landscapes provided that their application remains critically interpreted, context-sensitive, and embedded within professional planning expertise.

7 CONCLUSION

This paper set out to examine how data-driven and AI-supported analytical frameworks can be systematically operationalized within climate-adaptive landscape planning, using Riyadh as a representative case of an arid metropolis undergoing rapid spatial transformation. It demonstrates that AI and data-driven frameworks such as UrbAlytics, nAIture, and LIM landscape information modelling® are capable of translating heterogeneous environmental data into decision-relevant knowledge that can meaningfully support planning processes under conditions of climatic stress, spatial complexity, and time pressure. Rather than functioning as isolated technological enhancements, these frameworks operate most effectively when embedded within an integrated planning logic that links environmental data acquisition, modelling, simulation, and design intervention through iterative feedback loops.A central contribution of this research lies in advancing the understanding of those frameworks not as autonomous planning solution, but as methodological infrastructures that strengthens evidence-based reasoning in landscape and urban planning. By integrating Earth observation data, machine-learning-supported analytics, and structured information modelling, the proposed approaches enable environmental performance to be assessed, compared, and anticipated across multiple spatial and temporal scales. This represents a shift from predominantly descriptive and static assessments toward performance-oriented and predictive planning practices. In the context of arid megacities, where extreme heat, water scarcity, and ecological vulnerability interact in highly heterogeneous ways, such analytical precision is not merely advantageous but essential for informed decision-making.

The case of Riyadh illustrates how data-driven planning frameworks can address challenges that exceed the analytical capacity of conventional planning instruments. Rapid urban expansion, ambitious environmental targets, and compressed development timelines require methods that are scalable and capable of operating across large territories. The analytical ecosystems examined in this study demonstrate their suitability for these conditions by enabling the automated processing of large-scale datasets and the consistent comparison of alternative planning scenarios. Importantly, these capabilities do not replace design expertise or ecological judgement. Rather, the frameworks function as decision-support systems that enhance transparency, reveal trade-offs, and make complex environmental interdependencies legible to planners and stakeholders.

Beyond the specific case of Riyadh, the methodological implications of this research extend to climate-adaptive planning more broadly. The frameworks presented here are conceived as transferable approaches based on globally available data sources and adaptable modelling logic, making them applicable across diverse urban contexts facing increasing climatic uncertainty. At the same time, their effectiveness depends critically on data quality, model assumptions, and interpretive expertise, highlighting the continued importance of governance, transparency, and interdisciplinary oversight.

Taken together, the findings support a broader reframing of contemporary planning practice. Data-driven and AI-assisted methodologies should not be understood as optional technological add-ons, but as a necessary evolution of planning in response to the scale and complexity of climate-related challenges. Their primary value lies in augmenting human expertise by enabling anticipatory analysis, systematic scenario evaluation, and the alignment of spatial design decisions with long-term climate resilience and nature-positive objectives.

Future research should build on this foundation through longitudinal evaluation of implemented interventions, comparative studies across climatic regions, and deeper integration of social, governance, and equity dimensions into AI-supported planning frameworks. As cities continue to confront accelerating environmental change, the critical and responsible integration of AI into planning workflows will play a decisive role in shaping resilient, livable, and sustainable urban landscapes.

8 DATA AVAILABILITY STATEMENT

The data presented in this study is not available due to ongoing projects and confidentiality limitations.

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