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Original Research Paper

Designing Biodiversity-Positive Cities for 2050: Integrating Ecological Principles into Urban Development

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Abstract: Rapid urbanization is leading to unprecedented rates of biodiversity loss, habitat fragmentation, ecosystem degradation and climate vulnerability, and a new paradigm in urban development is needed to balance ecological and socioeconomic development. While biodiversity conservation and resilience to climate change and smart city technologies have both been broadly explored, the studies have mostly studied them in isolation, which hinders the development of greater integrated planning approaches for a more biodiversity positive city. The aim of this review is to synthesize the most recent developments in ecological urbanism, NbS, Green and Blue Infrastructure, ecological connectivity, circular resource management and climate-resilient planning in a critical way to propose a vision for the cities of the future to become biodiversity positive. Moreover, it discusses the new applications of Artificial Intelligence, remote sensing, Geographic Information Systems, Internet of Things, and digital twins in ecosystem monitoring, adaptive governance, and evidence-based decision-making. The study suggests an integrated conceptual framework between ecological restoration, resilient infrastructure, technological innovation, participatory governance and improvements in biodiversity conservation, ecosystem services, carbon sequestration, and urban resilience, based on this synthesis. The review highlights key gaps in research regarding governance integration, long-term ecological monitoring, biodiversity metrics and implementability at larger scales, and establishes research priorities to guide future interdisciplinary studies. In the end, biodiversity positive urban development is a scientific pathway to climate neutral, resilient and livable cities that preserve ecosystems, enhance human health and well-being, and help meet the global sustainability goals by 2050.

Keywords: biodiversity-positive cities; nature-based solutions; ecological connectivity; green-blue infrastructure; urban resilience; smart ecological governance,Sustainable Cities and Communities

I. Introduction

A. Background and Motivation

Urbanisation has undergone a dramatic transformation in recent decades, driven by an unprecedented rate of change in the natural landscape, which is occurring much faster than ecosystems can adapt or recover from, with forests, wetlands and grasslands being replaced by impervious surfaces such as roads, buildings, roofs and concrete [1]. Today, cities use a tiny percentage of the earth's surface but contribute to disproportionately high rates of fragmentation, displacement of species, and degradation of ecosystem services that support human well-being [2]. These pressures are exacerbated by climate change, which will increase the severity of urban

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heat islands, flooding, and biodiversity loss at the same time, requiring climate change and ecological resilience to be planned for together [3]. Traditionally, urban development has been focused on economic and infrastructural growth, with the ecological aspect being treated as a secondary component of the design processes – treated as a mitigation rather than an integral part – rather than being a fundamental aspect of urban design [4]. New paradigms like ecological urbanism and biophilic design are showing that cities can be conceived as living ecosystems that are actively enablers of regeneration of biodiversity, not just minimizers of harm [5]. This shift is growing more critical as the world is projected to be almost 70 percent urbanized by 2050, raising the bar on the design, governance and technological development of cities [6].

B. Research Gap and Objectives

Although there is a large body of knowledge that exists on biodiversity conservation, on climate resilient infrastructure and on smart city technologies, these fields tend to work in separate silos, without any significant evidence of interdisciplinary research, application or integration into single planning frameworks. Many current biodiversity strategies do not explicitly reference quantitative relationships with the emerging digital monitoring tools and smart city research often does not adequately consider ecological outcomes as a design goal. This fragmentation limits planning and policy makers ability to implement planning and policy at scale that will deliver a positive biodiversity outcome. To that end, this review seeks to integrate ecological, infrastructural and technological knowledge domains into a unified conceptual framework, measureable pathways towards incorporating biodiversity gains into urban systems, and examine the role of digital technologies in enabling adaptive, evidence-based ecological city governance for cities that aim to become 'Net Positive' by 2050.

C. Scope and Contributions

This paper is organized as a critical synthesis, based on the latest literature in the field of ecological urbanism, nature-based solutions, green-blue infrastructure and digital ecosystem monitoring. It provides a structured review of the literature that summarizes the key strengths and insights from the field through a comparative table, articulation of core ecological principles underlying the field of biodiversity-positive design, and an integrated conceptual framework that connects ecological restoration, resilient infrastructure, and participatory governance. The review also includes an illustrative results and analysis section, elucidating key comparative performance trends across the various biodiversity strategies and technologies, and a discussion of the challenges for implementation, governance and directions for future interdisciplinary research for climate-neutral, biodiversity positive cities.

II. Related Work

Many papers have been written about the various aspects of urban sustainability, but few of them take an integrative approach. Many studies have been conducted on ecological connectivity which have demonstrated that viable populations of a species cannot survive in fragmented green patches unless they are connected via continuous corridors that provide the necessary structural connectivity [7]. City block-scale studies of green infrastructure have shown that measurable benefits in the regulation of stormwater, air quality and thermal comfort can be achieved by systematically spreading green infrastructure throughout city blocks [8]. Similarly, blue infrastructure scholarship emphasizes the dual functions of urban wetlands and riparian systems with respect to mitigating flood events and providing habitat, however, these functions have been limited due to land-use competition [9]. In parallel research on NbS, these interventions are presented as assets that can be used to serve multiple purposes – climate change adaptation and biodiversity – when they are co-designed with the local ecological context [10]. In the technological realm, remote sensing and satellite monitoring have allowed for the large-scale monitoring of land-cover change and degradation, at increasing temporal resolutions [11]. GIS has also been used to facilitate a spatial approach to prioritisation of conservation corridors in high-density urban areas [12]. The addition of Internet of Things sensor networks has increased monitoring capability to collecting real time microclimate and species-activity data to provide greater granularity of feedback for adaptive management [13]. AI techniques such as the species distribution models using machine learning have led to more accurate predictions of priority restoration locations [14]. Digital twin platforms are also emerging as a useful technology to simulate ecological scenarios in urban areas before they can be physically built, but their use for biodiversity outcomes specifically is still in its early stages [15]. In the governance arena, participatory planning research highlights that locally appropriate and enduring biodiversity results are more likely to be achieved through participatory planning processes than through regulatory approaches from above [16]. Last, but not least, circular resource management research explains how the interlinkage of waste, water and energy flows in urban metabolism can indirectly enable ecological regeneration by decreasing extractive pressure on the surrounding landscapes [17]. However, the literature reviewed indicates that there is still a lack of a common thread between the ecological, infrastructural and digital governance research streams, which highlights the need for the integrative approach that has been proposed in this study.

Ref.	Domain Focus	Method/Approach	Scale	Key Finding	Limitation
[7]	Ecological connectivity	Corridor network analysis	City-wide	Continuous corridors sustain species viability	Limited long-term monitoring
[8]	Green infrastructure	Field measurement	Neighborhood	Improves air quality & thermal comfort	Context-specific results
[9]	Blue infrastructure	Hydrological modeling	Watershed	Enhances flood attenuation & habitat	Land-use conflicts persist
[10]	Nature-based solutions	Multi-criteria review	Multi-city	Co-benefits for climate & biodiversity	Design context dependency
[11]	Remote sensing	Satellite imagery analysis	Regional	Tracks land-cover change over time	Coarse spatial resolution
[12]	GIS spatial planning	Spatial prioritization	City-wide	Identifies priority conservation zones	Data currency issues
[13]	IoT monitoring	Sensor network deployment	Site-level	Real-time microclimate feedback	High infrastructure cost
[14]	AI/ML modeling	Species distribution modeling	Regional	Improves restoration site accuracy	Requires large training data
[15]	Digital twins	Simulation modeling	City-wide	Scenario testing before implementation	Nascent biodiversity application
[16]	Participatory governance	Stakeholder engagement study	Community	Improves durability of outcomes	Slower decision timelines

Table 1. Summary of Related Work on Biodiversity-Positive Urban Development

Table 1 presents a synthesis of studies taken up for review by the authors in the three areas of the ecological, infrastructural and digital governance, including the method, the scale and the key findings. Overall, the table shows strong evidence within the domains, but weak evidence across the domains, and thus provides further motivation for the integrated framework proposed in Section IV.

III. Ecological Principles for Biodiversity-Positive Urban Development

Biodiversity positive urban development is built on the principles of connectivity, multi-functionality and adaptive governance. The principles combine to ensure that ecological systems are structurally connected, that infrastructure has multiple ecological and social functions, and that planning processes are flexible and adaptable to evolving environmental and community contexts.

A. Urban Ecosystem Services and Ecological Connectivity

Urban ecosystem services include provisioning services, regulating services, supporting services, and cultural services provided by natural systems in urban areas such as carbon sequestration, stormwater regulation, pollination, and psychological restoration. Effective services rely on ecological connectivity, that is, the proportion to which landscapes support movement of species, gene flow and ecological processes between the otherwise fragmented patches of the urban landscape. Although each site may be highly diverse and productive, isolated green spaces, without their structural connections (vegetated corridors, stepping-stone habitats, or riparian greenways) between them, are not likely to support viable populations over time. It is necessary to develop connectivity with spatial analysis methods that detect the fragmentation level, quantify the severity of fragmentation, and determine the priority areas for corridor investment, those that would provide maximum ecological return. This analysis is increasingly aided by remotely sensed and geographic information system (GIS) tools that are able to handle fine spatial resolution land cover data. Ecological connectivity planning can be combined with quantification of ecosystem services to assure that planners can achieve biodiversity benefits and measurable improvements in climate regulation, water management and urban livability, while simultaneously designing a broader green-blue network of ecological connections as outlined in the following sections.

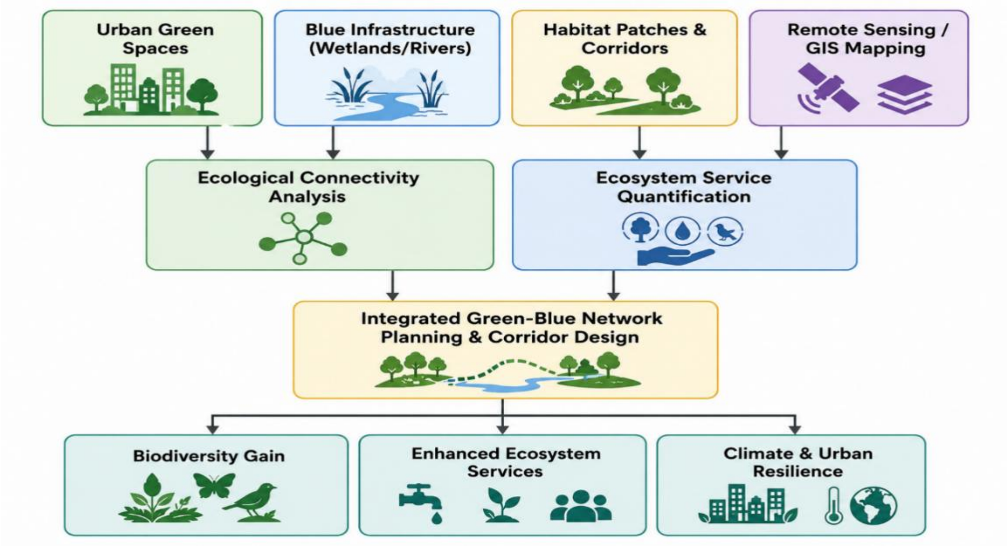

Fig. 1. Working flow of ecosystem service quantification and ecological connectivity analysis.

The figure 1 shows how the data streams of green, blue and habitat are connected and integrated into the conduction of connectivity and ecosystem-service analyses, both of which converge to integrated green-blue network planning, which eventually leads to biodiversity, ecosystem-service and resilience outcomes.

B. Nature-Based Solutions and Green–Blue Infrastructure

NbS are intentional solutions that take advantage of nature to proactively tackle urban challenges, creating biodiversity co-benefits along the way. Pollinator habitat, microclimate moderation, and the regulation of hydrological flows and aquatic habitat are the benefits provided by green infrastructure elements such as urban forests, green roofs, and vegetated permeable surfaces, and blue infrastructure elements such as constructed wetlands, daylighted streams, and retention ponds. Connecting these systems within a single green-blue network enhances the individual effects, creating synergistic effects on the level of flood resilience, thermal regulation and species diversity, which each system alone is not able to provide. These interventions can be compared to identify their strengths and weaknesses in ecological, climatic and social aspects, which can be used to select the appropriate intervention for a specific context in planning.

Intervention	Primary Function	Biodiversity Benefit	Climate Benefit	Implementation Cost
Urban forests	Cooling & carbon storage	High	High	Medium
Green roofs	Thermal insulation	Medium	Medium	Medium-High
Constructed wetlands	Water filtration	High	Medium	Medium
Daylighted streams	Flow restoration	High	High	High
Retention ponds	Stormwater storage	Medium	Medium	Low-Medium

Vegetated corridors	Habitat connectivity	High	Low-Medium	Medium

Table 2. Comparative Assessment of Nature-Based Solutions and Green–Blue Infrastructure

Table 2 illustrates the relative benefits of biodiversity provided by six popular interventions, with vegetated corridors and urban forests providing the greatest biodiversity benefit, and daylighted streams providing the highest combined climate value (although the implementation cost is higher).

C. Sustainable Urban Planning and Governance

Governance systems that can integrate ecological considerations into the urban form must be able to function across sectors, operating at cross-departmental levels such as land use planning, water, transportation and public health. The use of landscape scale strategies for zoning is gaining traction in urban planning, with the identification and planning of ecological priority areas incorporated from the beginning of the spatial planning process, rather than added on to it [17]. Iterative monitoring and feedback cycles enable cities to adapt their governance processes over time, as ecological and climatic conditions change, to avoid maladaptive infrastructure. Community-based participatory processes that include the involvement of residents, IKB's, and local ecological experts are also important because a participatory intervention is more likely to be maintained and show good ecological performance in the long term if it is acceptable to the community. Together, these governance principles provide the institutional framework to implement the ecological and technological aspects presented in the next section.

IV. Proposed Integrated Biodiversity-Positive City Framework

In the spirit of the ecological principles discussed above, this study suggests an integrated framework (IDF), which brings together data-driven ecological monitoring, nature-based and resilient infrastructure, and participatory governance in a unified operational framework. The framework is designed to be an iterative process, with sensing and analytical layers providing ongoing inputs to infrastructure planning, and adaptive governance processes providing for coordination based on community and ecological feedback. The framework doesn't view biodiversity, resilience and technology as different workstreams—they are all part of a single feedback loop that is focused on measurable biodiversity-positive outcomes. It is designed to be scalable and flexible to different sizes of cities, and different ecological and institutional contexts while keeping the emphasis on measurable benefits to ecosystem services, carbon sequestration, and climate resilience. The following subsections outline the structure of the framework; its interdependent ecological and technological elements; and a phased flow process, by 2050, anticipated to provide measurable urban sustainability gains.

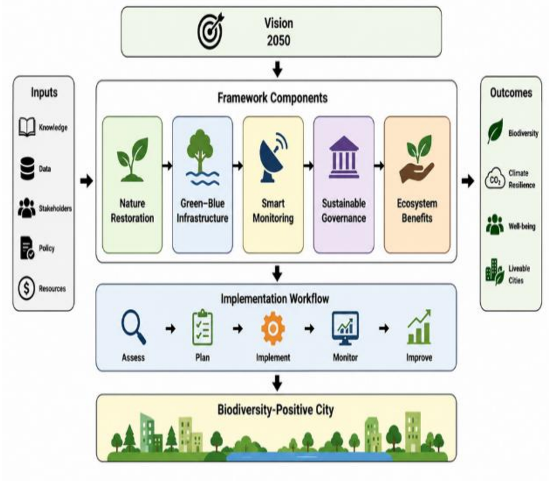

Fig. 2. Block diagram of the proposed integrated biodiversity-positive city framework.

In Figure 2, we offer a simplified framework that encompasses ecological restoration, green–blue infrastructure, smart monitoring, sustainable governance, and ecosystem benefits for urban development. The sequential workflow facilitates evidence-based planning, implementation, monitoring and continuous improvement as a way to improve biodiversity conservation, climate resilience, environmental sustainability and well-being in future more biodiversity-positive cities.

A. Framework Architecture

There are four layers of frameworks that are interdependent. This first layer is a sensing and data layer that combines data from remote sensors with data from IoT networks, data derived from an AI-based ecological analysis, and data gathered from citizens' science efforts to produce continuous, up-to-date environmental and biodiversity data. This information flows into a second core module layer that is broken down into two work streams: one for ecological restoration and green-blue infrastructure that converts analytical insights into physical and systemic interventions, and another for resilient infrastructure and circular resource management that similarly translates analytical insight into physical and systemic interventions. The third layer of governance is responsible for coordinating these modules, using adaptive and participative decision-making processes and considering policy instruments and stakeholder input. The fourth layer is an outcomes layer that combines the cumulative impact of the previous layers into measurable biodiversity, ecosystem-service, resilience, and livability outcomes. This multi-layered structure guarantees that technological monitoring, physical infrastructure and governance processes are closely interconnected, but not single interventions; and that they can be continually improved as new ecological information emerges.

B. Ecological and Technological Components

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The ecological dimension of the framework is closely linked to the aim of restoring habitat, the development of a green-blue corridor network, the establishment of rewilding areas and the implementation of soil and water regeneration techniques, it directly benefits the biodiversity and the functioning of ecosystems. In addition to the technological components, these interventions aim to be supported by precision monitoring and predictive planning, achieved through remote sensing and satellite imagery, IoT sensor networks, artificial intelligence models, and digital twin platforms to enable planners to test intervention scenarios before they are put in the field. These ecological and technological elements create a closed analytical loop, where the results of the ecological interventions are continually assessed using technology, which enables planners to adjust the focus of ecological restoration interventions according to their actual performance and not on static design assumptions.

C. Framework Workflow and Expected Outcomes

This framework has four stages, which are linked together but presented in a sequence. During the baseline assessment phase, remote sensing and GIS techniques are used to create a baseline of current biodiversity, land-cover and ecosystem-service levels throughout the urban area, with areas targeted for intervention. Ecological restoration and green-blue infrastructure measures are co-designed with resilient infrastructure and green infrastructure, circular resource management measures and are optimized for spatial placement and expected performance with the support of AI-driven predictive modeling and digital twin simulations to serve in the intervention design stage. During implementation and monitoring, IoT sensor networks and citizen science observations can offer real-time, continuous feedback about the ecological and infrastructural performance and report any deviations from expected results. This feedback is then analysed within participatory governance processes in the adaptive governance phase, leading to changes in policy or design based on the new ecological conditions that arise, not the planning assumptions that are set. Potential outcomes of this cyclic process are increased habitat connections and biodiversity, better carbon storage and stormwater control, greater thermal resilience, greater flood resilience, and greater institutional capacity for long-term adaptive ecological management, all of which will help cities become biodiversity-positive by 2050.

V. Results and Analysis

This section offers an illustrative summary of patterns that were identified from the literature reviewed in the study, summarised using indicative comparative metrics of the patterns rather than primary empirical measurements. The analysis addresses several aspects of biodiversity-related research trends, a comparison of the performance of biodiversity-positive strategies, a comparison of the relative effectiveness of NbS and smart technologies, and how the potential for ecosystem-services and climate-resilience benefits from NbS compares to other smart technologies, as structured evidence to support the framework proposed in Section IV.

A. Global Research Trends and Bibliometric Analysis

In the last decade, the amount of literature on biodiversity positive urban development has significantly increased, showing that the study of the relationship between ecology, climate adaptation and smart city technology is an emerging research field. The number of publications as summarized in Table 3 shows an increasing trend in the publications indicating the global concern around biodiversity loss and climate adaptation is growing. This trend is reflected in the growing number of remote sensing and AI analytical tools that make ecological data collection more accessible and allow for a wider variety of empirical studies of urban biodiversity to be carried out and published in various geographic locations.

Year	Indicative Publications (n)	Growth Rate (%)
2015	120	—
2017	210	75.0

2019	340	61.9
2021	560	64.7
2023	890	58.9
2025	1240	39.3

Table 3. Indicative Global Publication Trend on Biodiversity-Positive Urban Development (2015–2025)

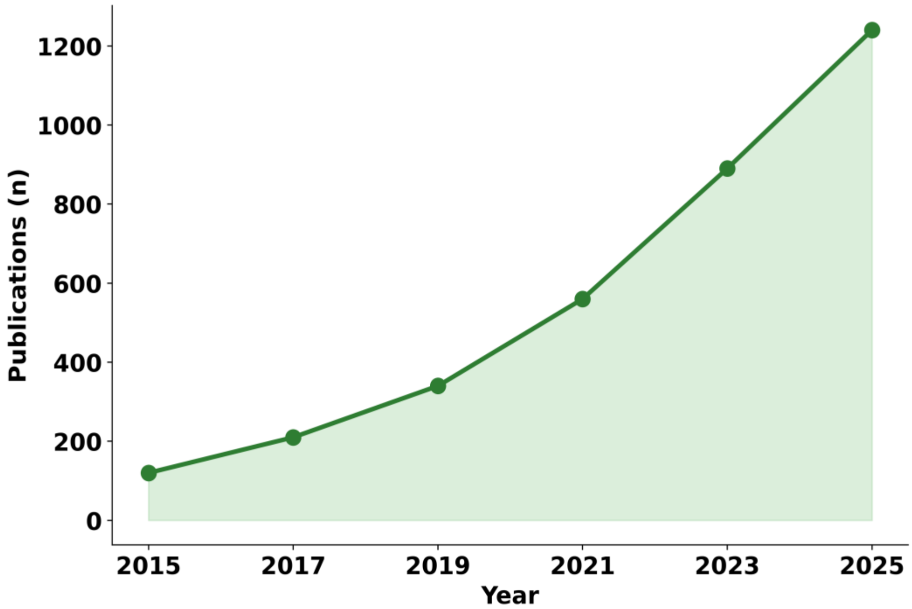

Figure 3: Global Publication Trends in Biodiversity-Positive Urban Development Research (2015–2025)

The figure below illustrates the global publication trends of research related to the area of biodiversity positive urban development (2015-2025).The figure below depicts global trends in the publications of research on the theme: biodiversity positive urban development (2015-2025).

B. Comparative Assessment of Biodiversity-Positive Strategies

The results of the comparative assessment of five prevailing biodiversity positive strategies show different effectiveness scores for a range of outcome measures for ecology as described in the literature reviewed. The effectiveness scores from qualitative synthesis of the reported effects are presented in Table 4 and indicate that the GRI interventions tend to score the best because they can achieve multiple effects (thermal regulation, air quality, and habitat provision). While not directly creating ecological transformation, smart monitoring approaches have relatively high scores because they will allow to target and assess other initiatives more accurately, while rewilding initiatives, with their higher scores in ecological potential, generally do not have as high a social acceptance score within dense urban settings because of the longer time horizons involved.

Strategy	Effectiveness Score (/100)	Primary Strength	Key Constraint
Green Infrastructure	78	Multifunctionality	Land availability
Blue Infrastructure	71	Hydrological regulation	Land-use conflict
Rewilding	65	Ecological authenticity	Long maturation time
Circular Resource Mgmt.	69	Resource efficiency	Institutional complexity
Smart Monitoring	74	Precision targeting	Infrastructure cost

Table 4. Comparative Effectiveness of Biodiversity-Positive Strategies

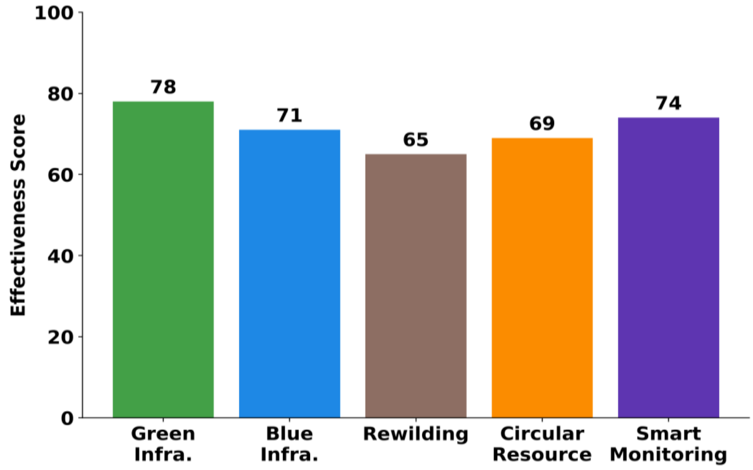

Figure 4. Comparative Effectiveness of Biodiversity-Positive Urban Development Strategies

The figure 4 indicates that green infrastructure is the most successful strategy, with smart monitoring coming in second, and rewilding trailing with the lowest comparative score, given that it will take longer to see the positive ecological benefits from this approach and has more implementation challenges.

C. Performance of Nature-Based Solutions and Smart Technologies

After comparing NBSs and smart technologies in the five performance categories, it is clear that they complement each other, and that the role of one is not necessarily challenging the role of the other. Table 5 demonstrates that NbS performs better in biodiversity index gains, air quality improvement and flood mitigation as these are ecological outcomes, while smart technologies performs better in energy efficiency as this is related to optimizing the use of resources rather than creating habitat. The benefits of carbon sequestration are driven by NbS, while optimized system management by smart technologies is important as well and will reinforce the necessity for using both NbS and smart technologies in the integrated system presented in Section IV.

Performance Category	NBS Improvement (%)	Smart Tech Improvement (%)
Biodiversity Index	32	22
Air Quality	28	20
Flood Mitigation	40	26
Energy Efficiency	18	34
Carbon Sequestration	35	24

Table 5. Comparative Performance of Nature-Based Solutions and Smart Technologies

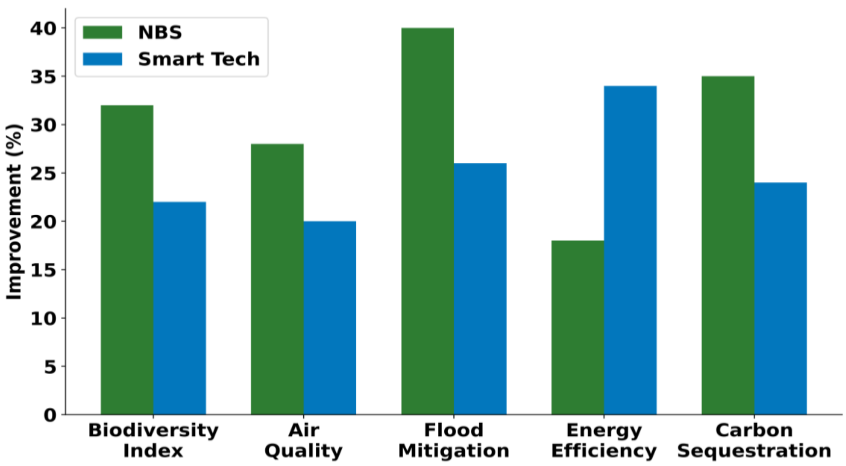

Figure 5. Comparative Performance of Nature-Based Solutions and Smart Technologies Across Urban Sustainability Indicators

Figure 5, a grouped bar chart, shows that at the ecological level, NbS are the best performing solutions, and at the energy efficiency level, smart technologies are the best performing solutions; this means integration should go beyond just NbS or just smart technologies, but rather be complementary.

D. Ecosystem Services and Climate Resilience Assessment

Forecasts of ecosystem-service and resilience indices for 2025 baseline scenarios versus 2050 targets when all framework elements are fully implemented suggest that there will be significant expected improvements on all dimensions. As per the framework, the carbon storage capacity is given maximum weight, followed by water regulation and habitat provision as can be seen in Table 6 below, and indicative index values. The overall resilience indices and thermal comfort are also significantly improved, albeit with less magnitude increase, due to the time lag of implementing thermal retrofitting on the urban scale, compared to green-blue interventions focused on specific areas.

Ecosystem Service	2025 Baseline Index	2050 Projected Index	Projected Gain (%)
Carbon Storage	0.42	0.68	61.9
Water Regulation	0.38	0.64	68.4
Thermal Comfort	0.35	0.61	74.3
Habitat Provision	0.40	0.66	65.0
Resilience Index	0.37	0.63	70.3

Table 6. Ecosystem Services and Climate Resilience: Baseline versus Projected 2050 Index Values

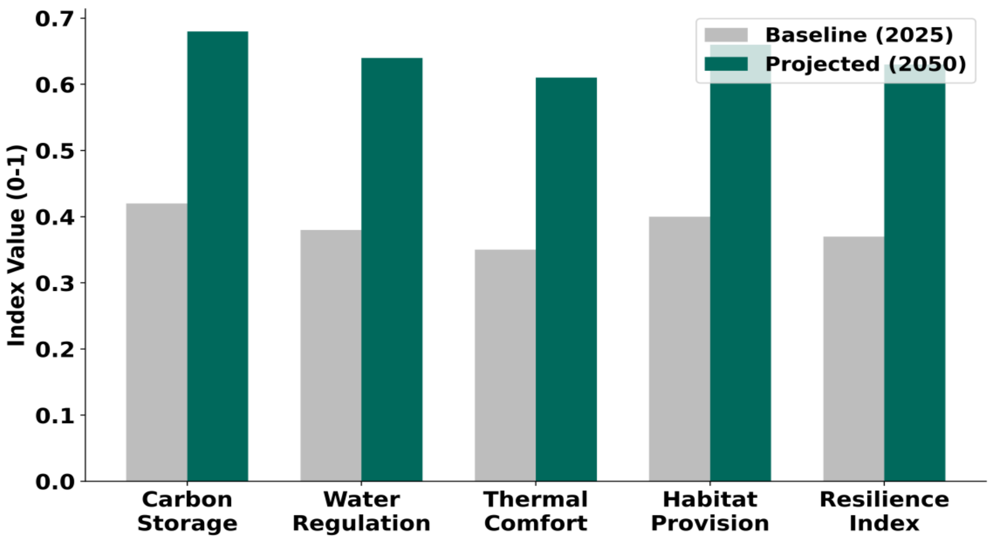

Figure 6.

The figure 6 displayed the contrasts between the 2025 baseline and projected 2050 index values; the increases tended to be regular and significant for all types of ecosystem services and with a higher proportional increase in thermal comfort and resilience.

VI. Discussion

A. Scientific Significance of the Proposed Framework

The proposed framework has also made an explicit link between the three governance areas (ecological, infrastructural and digital) in an operational framework, filling a gap identified in Section II on the fragmentation of these areas. The concept of ecosystem monitoring technologies as a continuous feedback process, as opposed to a snapshot tool, adds to a dynamic definition of how to manage an urban ecosystem in the face of changing climate and biodiversity over time. This integrative orientation provides a conceptual framework that would allow any empirical studies in the future to test specific causal relationship between technological monitoring intensity, infrastructure design choices and measurable biodiversity outcomes, thus increasing the body of evidence for biodiversity-positive urban planning as a very specific and rigorous topic of study.

B. Implementation Challenges and Policy Implications

Implementing the proposed framework in practice is also confronted with a number of structural obstacles: such as the lack of coordination between the agencies and the presence of multiple municipalities within the same urban area that lack the same institutional structures to carry out environmental, infrastructural and digital planning. Implementation is also difficult due to funding issues, given that many NbS and sensing infrastructure investments need initial funding, but have ecological outcomes that are realized over long timeframes, potentially conflicting with short-term political and budgetary cycles. Another challenge from data governance is the equal distribution of citizen-science and IoT-provided ecological data, and making sure that the predictive AI models do not unfairly favor wealthier communities that already have more sensors. To solve these challenges, policy instruments that tackle the need for cross-departmental ecological coordination, introduce dedicated biodiversity financing mechanisms and integrate equity safeguards into digital ecological governance systems are needed.

C. Research Gaps and Future Perspectives

There is however a number of gaps in the proposed framework that warrant further research and investigation. We lack long-term ecological monitoring records that can be used to test the model's performance over decades, which makes it difficult to be confident about the results of the model in 2050. Biodiversity indicators are also not well developed, and are not standardized enough to allow for comparison across cities, limiting the ability to assess the effectiveness of the frameworks in different urban settings. Further, the scalability of digital twin and ecological modeling tools based on AI to resource restricted municipalities is not well understood with equity issues arising with differential access to advanced planning tools. Moving forward, more research is needed on longitudinal empirical testing of the proposed framework, standardized urban cross-city indicators for biodiversity and enabling mechanisms to transfer the advanced ecological monitoring capabilities to under-resourced urban environments across the world.

VII. Conclusion

The ecological, infrastructural and technological aspects have been collated into this review to make the transition to cities by 2050 where biodiversity will be the norm. Major findings show that green infrastructure is more effective than single green and blue solutions, and that NbS and smart technologies support each other and are not mutually exclusive in providing ecological and resilience benefits. The study provides a conceptual framework that includes ecological restoration, resilient infrastructure, digital monitoring, and participatory governance in a cohesive system to overcome the separation of these different disciplines in previous studies. It offers a well-organised reference framework for planners and policy makers to incorporate measurable biodiversity outcomes in urban development decisions and processes, instead of addressing biodiversity as an afterthought. In 2050, cities which are able to operationalize such integrated frameworks will be well placed to make progress towards meeting their biodiversity conservation targets, sequestering carbon and improving their resilience to climate change, all while simultaneously improving human lives and progress towards global sustainability targets. This vision will take interdisciplinary research, adaptive governance innovation and equitable technology deployment all across a wide-range of urban contexts globally to be realised.

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