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Optimization and improvement strategies for urban ecological space

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Abstract: The optimization of urban ecological space is increasingly constrained by compact urban development and environmental stress, revealing the limitations of conventional planning approaches that rely on fragmented green space protection and static indicators. This study proposes a GIS-based spatial analysis framework to evaluate and optimize urban ecological space through spatially explicit assessment, indicator-based comparison, and scenario testing. The methodology integrates spatial data processing, ecosystem service proxies, and multi-criteria spatial evaluation within a unified GIS environment. Ecological structure is assessed through fragmentation and connectivity metrics, ecosystem service potential is estimated using spatial proxies for cooling, runoff retention, and green space provision, and spatial equity is evaluated through accessibility thresholds and service distribution. Based on baseline spatial analysis, multiple optimization scenarios are constructed by modifying green infrastructure configuration under compact growth constraints. The results demonstrate that GIS-based scenario comparison enables measurable improvements in ecological connectivity, ecosystem service efficiency, and spatial performance. By transforming urban ecological optimization from a strategy-driven concept into a spatially testable and decision-oriented process, the proposed framework provides transferable analytical support for sustainable, resilient, and human-centered urban ecological development.

Keywords: City 1; Growth 2; Aesthetics 3; Intelligence 4; Digital 5

1. Introduction

Urban ecological space is increasingly challenged by compact urban growth, environmental stress, and rising demands for ecological services, exposing the limitations of conventional planning approaches that treat green space as fragmented and static entities(Kaplan, 2010). While urban growth strategies, aesthetic considerations, and digital technologies have each contributed to improving urban environments, their integration has often remained conceptual rather than spatially testable, limiting their effectiveness in guiding ecological optimization(Bareis & Droste, 2013; Herman, Sbarcea & Panagopoulos, 2018).

Recent advances in digital technologies and intelligent systems have expanded the capacity to monitor and manage urban environments (Akbari et al., 2015). However, without a spatially explicit analytical framework, data-driven tools such as sensors, artificial intelligence, and environmental monitoring systems struggle to translate information into actionable spatial strategies. In this context, the central challenge is not the lack of data or technology, but the absence of a spatial method capable of evaluating how ecological structure, ecosystem service performance, and urban form interact across continuous urban space.

This study addresses this gap by positioning GIS-based spatial analysis as the core methodological approach for optimizing urban ecological space. Rather than approaching urban growth, aesthetics, and intelligence as independent domains, the research reframes them as spatial variables that can be analyzed, compared, and reconfigured through GIS. By applying spatial metrics, ecosystem service proxies, and scenario-based evaluation, the

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proposed framework enables ecological performance to be assessed across a continuous urban terrain, linking spatial configuration with environmental function and human experience.

The key innovation of this research lies in transforming urban ecological optimization from a strategy-driven and descriptive process into a spatially explicit, scenario-tested analytical system. Through GIS-based evaluation and decision-oriented spatial outputs, the study provides a transferable framework for improving ecological resilience, environmental quality, and urban livability under compact development constraints.

2. GIS-based Spatial Analysis Framework for Urban Ecological Space Optimization

Urban ecological space optimization is addressed through a GIS-based spatial analysis framework (**Figure 1**) that integrates spatial structure assessment, ecosystem service evaluation, and scenario-based decision support within a unified analytical environment. Rather than treating conserved ecosystems, green infrastructure, wetlands, and agricultural land as isolated elements, the framework conceptualizes urban ecological space as a continuous spatial system whose performance can be evaluated, compared, and optimized through spatial metrics and modelling.

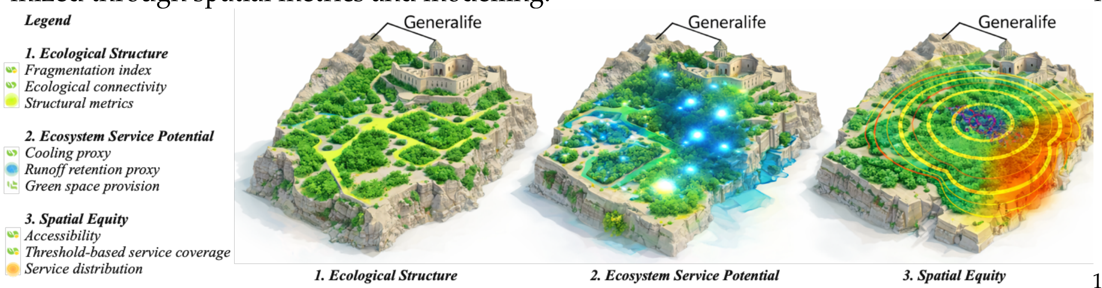

Figure 1. Spatial Evaluation of Urban Ecological Space Using GIS-Based Analysis.

The spatial configuration of urban ecological land is examined through GIS-based structural analysis. Fragmentation patterns, connectivity deficits, and spatial mismatches between ecological land and urban growth are identified using spatial metrics and network-based analysis. Ecological connectivity is treated as a core analytical variable, allowing conserved ecosystems and green infrastructure to be evaluated in terms of system-level spatial coherence rather than individual patch preservation.

Ecosystem service potential is assessed through spatially explicit proxy indicators derived within the GIS environment. Ecosystem service efficiency is defined as the relative ecological performance generated per unit of ecological space, considering both spatial stock and functional distribution. Urban ecological land is categorized into recreational, stocked, and distributed green space according to service function and spatial role. Cooling potential, runoff retention capacity, and green space provision are estimated through spatial proxies and modelling tools, including GIS-based ecosystem service assessment workflows. Scenario-based comparison is applied to evaluate how alternative spatial configurations influence ecosystem service efficiency and demand–supply balance.

Spatial scenarios are constructed by modifying green infrastructure configuration and connectivity patterns while maintaining compact urban growth constraints. A baseline spatial condition serves as the reference state for comparison. Each scenario is evaluated through a multi-criteria spatial assessment that integrates structural connectivity, ecosystem service performance, and spatial equity indicators. The results are translated into spatial priorities and intervention zones that support planning-oriented decision-making.

This framework establishes a transferable GIS-based approach that shifts urban ecological space optimization from strategy-driven abstraction toward spatially explicit evaluation and scenario-tested decision support.

3. Results: Optimization and Improvement Outcomes

The GIS-based spatial analysis demonstrates that targeted spatial optimization leads to measurable improvements in ecological structure and ecosystem service performance. Scenario-based comparison shows that enhanced green infrastructure configuration increases ecological connectivity, reduces patch isolation, and improves corridor continuity across the urban terrain. Fragmentation indices and connectivity metrics indicate a clear shift from disconnected ecological patches toward a more coherent ecological network structure under optimized scenarios.

In mountainous and rapidly urbanizing contexts, spatial indicators reveal that ecosystem service efficiency increases following optimization. Indicator-based evaluation shows that areas characterized by medium-level ecosystem service demand benefit most from improved spatial configuration, where relatively small structural adjustments generate disproportionate gains in cooling potential, runoff retention, and green space provision. The differentiated spatial allocation of recreational, stocked, and distributed green land produces complementary effects, enhancing both environmental regulation capacity and accessibility to ecological services.

At the planning and governance interface, spatial evaluation highlights the role of green infrastructure-oriented planning controls in improving ecological performance. The integration of landscape pattern indicators and ecosystem service proxies into spatial assessment enables clearer identification of priority intervention zones and performance gaps. Scenario evaluation demonstrates synergistic effects across ecological structure, ecosystem service provision, and environmental quality, supporting planning decisions that align spatial configuration with ecological and social objectives.

3.1. Spatial Differentiation of Ecological Structure under Scenario-Based Optimization

These results demonstrate that ecological structure within the Alhambra palace complex cannot be meaningfully understood or optimized through aggregate indicators alone. GIS-based spatial differentiation reveals that connectivity gains are highly uneven across the terrain, with corridor continuity and fragmentation reduction emerging selectively in topographically constrained zones. This finding confirms that ecological coherence in heritage landscapes is a spatially contingent condition rather than a uniform outcome, and that scenario-based GIS analysis is essential for identifying where structural interventions are both effective and spatially feasible. In this sense, GIS does not merely support ecological optimization but actively defines its spatial limits and opportunities.

3.2. Scenario-Driven Variation in Ecosystem Service Performance and Spatial Equity

The scenario-driven evaluation shows that ecosystem service performance and spatial equity respond nonlinearly to spatial reconfiguration within the Alhambra context. GIS analysis makes visible how modest structural adjustments can generate disproportionate gains in cooling, runoff regulation, and service accessibility in specific locations, while producing limited effects elsewhere. This uneven response underscores that ecosystem service efficiency is fundamentally a spatial property shaped by configuration, demand distribution, and terrain conditions. By revealing these spatial trade-offs, GIS enables optimization strategies to move beyond generic improvement targets toward site-sensitive, equity-aware decision-making grounded in spatial evidence.

Table 1. GIS-Enabled Synthesis of Spatial Optimization Insights in the Alhambra Context.

Analytical Dimension	GIS-Revealed Spatial Insight	Why GIS Is Essential	Implication for Optimization
Ecological structure	Connectivity improvements occur selectively across the terrain rather than uniformly across the system	Only spatial indicator comparison reveals where fragmentation reduction and corridor continuity are feasible	Structural interventions must be spatially targeted rather than system-wide

Terrain constraint	Topography conditions the effectiveness of ecological corridors and connectivity gains	GIS integrates terrain, configuration, and network metrics within a single analytical space	Optimization strategies must be terrain-sensitive to avoid ineffective interventions
Ecosystem service performance	Service gains respond nonlinearly to spatial reconfiguration, with disproportionate effects in specific zones	Scenario-based GIS analysis identifies spatial trade-offs and uneven responses	Ecosystem service efficiency depends on configuration, not green space quantity alone
Spatial equity	Improvements in service accessibility vary spatially, revealing persistent gaps under certain scenarios	GIS makes inequities visible through accessibility thresholds and demand distribution	Equity-oriented optimization requires spatial prioritization, not average performance gains
Decision support	Priority intervention zones emerge only when multiple spatial indicators are evaluated together	GIS enables integration of structure, services, and equity within scenario comparison	Planning decisions benefit from spatially explicit, evidence-based prioritization

4. Conclusion

This study demonstrates that urban ecological space optimization can be more effectively addressed through a GIS-based, system-oriented analytical framework that integrates spatial restructuring, ecosystem service efficiency, and planning coordination (Kaplan, 2010; Herman, Sbarcea & Panagopoulos, 2018). By enabling spatially explicit evaluation, indicator-based comparison, and scenario testing, GIS-based spatial analysis supports a shift from isolated green space protection toward holistic ecological optimization, enhancing urban environmental performance and ecological resilience under compact urban conditions.

At the same time, the results indicate that the effectiveness of ecological optimization is closely linked to the capacity to continuously update spatial data, indicators, and scenarios within the planning process. Constraints such as fragmented governance structures, regulatory inconsistencies, and implementation capacity can be more explicitly identified and evaluated when ecological performance is assessed spatially rather than conceptually.

Future research should further develop GIS-enabled adaptive governance frameworks by integrating dynamic ecological monitoring, scenario updating, and participatory spatial tools. Strengthening the coupling between spatial analysis and planning institutions will be essential for improving the long-term resilience, equity, and sustainability of urban ecological systems.

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