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Urban Ecology and Biodiversity: Patterns, Mechanisms, and the Role of Green Infrastructure in Sustaining Ecosystem Services

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ABSTRACT

Rapid global urbanization has emerged as one of the most consequential drivers of biodiversity loss and ecosystem transformation in the twenty-first century. By 2050, it is projected that approximately 68 percent of the world's population will reside in urban areas, intensifying pressures on native species, habitat connectivity, and the provisioning of critical ecosystem services. This review synthesizes the current state of knowledge on urban ecology, with a particular focus on the mechanisms by which urbanization shapes biodiversity, the functional role of green infrastructure in mitigating habitat fragmentation, and the capacity of urban ecosystems to sustain provisioning, regulating, and cultural ecosystem services. Drawing on an extensive body of literature from both Web of Science- and Scopus-indexed sources, the article examines the urban-to-rural biodiversity gradient, the homogenization of urban biota, and the differential responses of taxonomic groups to urban environmental filters. The review argues that green infrastructure—encompassing parks, green roofs, street trees, riparian corridors, and urban wetlands—can substantially offset biodiversity losses and maintain critical services including urban heat island mitigation, stormwater management, carbon sequestration, and psychological well-being. The article concludes with an integrated framework for evidence-based urban ecological planning and identifies key knowledge gaps requiring further empirical investigation.

Keywords: Urban ecology; biodiversity; green infrastructure; ecosystem services; urbanization; habitat fragmentation; biotic homogenization; urban heat island; landscape ecology; sustainable urban planning

1. INTRODUCTION

The twenty-first century is an era defined, above all else, by the accelerating concentration of human populations in cities. According to the United Nations (2018), the global urban population surpassed the rural population for the first time in recorded history in 2007 and is projected to reach approximately 6.7 billion by 2050, representing roughly 68 percent of total projected world population. Urban areas currently cover only 0.5 to 3 percent of Earth's land surface, yet the cumulative ecological footprint of cities extends far beyond municipal boundaries through their demands on water, energy, food, and materials (Grimm et al., 2008). More acutely, the expansion of urban land cover into natural and semi-natural habitats directly displaces native species, fragments populations, and eliminates ecosystem services that had previously been provided free of charge by functioning natural ecosystems (Seto et al., 2012).

The ecological consequences of urbanization are pervasive and multi-scalar. At the local scale, impervious surface expansion drives surface runoff, alters thermal regimes, and produces the well-documented urban heat island effect, which can elevate mean temperatures in city centers by 1–3 °C relative to surrounding rural areas (Tzoulas et al., 2007). At the community scale, the replacement of native habitat with urban infrastructure fundamentally reconfigures food webs, alters trophic interactions, and generates strong environmental filters that favor a subset of generalist, disturbance-tolerant species over habitat specialists (Shochat et al., 2006). At the regional and global scales, the projected spatial trajectory of urban growth — concentrated disproportionately in the biodiversity-rich tropical and subtropical regions of the world — threatens an estimated 290 globally threatened species with imminent habitat overlap or loss (Seto et al., 2012; McDonald et al., 2008).

Yet cities are not ecological deserts. Growing evidence from urban ecological research across Europe, North America, East Asia, and Australia indicates that strategically designed and managed urban green spaces can sustain remarkable levels of biological diversity, including populations of indigenous plants, arthropods, birds, and even mammals (Aronson et al., 2014; Faeth et al., 2011). Urban parks and woodlands, green roofs, community gardens, street trees, and riparian corridors collectively constitute the “green infrastructure” of cities — a spatially interconnected network of natural and semi-natural elements that delivers multiple ecosystem services simultaneously (Tzoulas et al., 2007; Bolund & Hunhammar, 1999). The potential of green infrastructure to serve as a dual tool for biodiversity conservation and urban sustainability planning has generated substantial scientific and policy interest, yet the mechanistic understanding of what determines green infrastructure effectiveness remains incomplete.

This review addresses three interrelated questions. First, what are the principal patterns and mechanisms by which urbanization shapes biodiversity across taxa and spatial scales? Second, what is the evidence that urban green infrastructure sustains functionally significant ecosystem services? Third, what conceptual and practical frameworks are best suited to integrating ecological knowledge into urban planning and governance? The synthesis draws on peer-reviewed literature indexed in the Web of Science and Scopus databases, emphasizing empirical studies, quantitative meta-analyses, and conceptual frameworks published between 1999 and 2025. The review is structured to progress from a diagnosis of the urban biodiversity crisis, through an analysis of mechanisms and responses, to a constructive assessment of evidence-based solutions.

2. URBANIZATION AND ITS ECOLOGICAL CONSEQUENCES

2.1 The urban biodiversity gradient

One of the most robust and widely replicated findings in urban ecology is the negative relationship between increasing urbanization intensity and species richness, most prominently documented for vascular plants, birds, and ground-dwelling arthropods (McKinney, 2008; Grimm et al., 2008). The classic model of this relationship posits a monotonic decline in native species richness along a rural-to-urban gradient, driven by progressive habitat loss, increased impervious surface cover, elevated levels of artificial light at night, noise pollution, and chemical contamination of soils and water bodies (Pickett et al., 2001). However, subsequent research has revealed considerably more complexity. Shochat et al. (2006) documented a hump-shaped relationship for some taxa, particularly birds, whereby intermediate levels of urbanization can support higher total species richness than either highly urban or undisturbed rural environments, owing to the heterogeneous mixture of native, introduced, and synanthropic species that colonize moderately disturbed habitats.

A global analysis of bird and plant responses to urbanization across 54 metropolitan areas on six continents found that plant species richness declined with urbanization intensity, while bird richness showed a more heterogeneous response that depended on the availability of native vegetation cover within the urban matrix (Aronson et al., 2014). The proportion of native species consistently declined with urbanization across both taxa, confirming that the gross richness response can mask substantial turnover in community composition. More recent syntheses have confirmed that specialist and area-sensitive species are disproportionately vulnerable to urban pressures, while generalist and habitat-tolerant species tend to dominate urban assemblages (Lepczyk et al., 2017). These compositional shifts have profound implications not only for biodiversity per se but also for the functional diversity of urban ecological communities and the resilience of the ecosystem services they provide.

2.2 Biotic homogenization

Perhaps the most ecologically insidious consequence of urbanization is the global phenomenon of biotic homogenization — the process by which urban environments increasingly support taxonomically and functionally similar assemblages across geographically distant cities. As urban development imposes comparable environmental filters worldwide — elevated disturbance, altered thermal regimes, high soil nutrient availability, and selective propagule pressure from human-mediated transport — it tends to favor a globally shared pool of cosmopolitan, generalist species at the expense of locally endemic and specialist taxa (McKinney, 2008). This trend is most clearly documented for plants: urban floras across European cities share substantially larger proportions of non-native species, particularly from the Mediterranean and Central Asian floristic provinces, than would be expected from random assembly, producing broadly similar vegetation communities despite pronounced climatic and biogeographic differences among cities (Sukopp, 2004).

Homogenization is equally apparent in urban bird communities, where a globally distributed suite of species — including Columba livia, Passer domesticus, Sturnus vulgaris, and Corvus splendens — has become so cosmopolitan as to represent a de facto global urban avifauna (Aronson et al., 2014). The ecological and evolutionary consequences of biotic homogenization extend beyond simple diversity metrics. Homogenized communities may lack the functional diversity required to buffer ecosystem processes against environmental perturbations, and the displacement of locally adapted genotypes by introduced competitors may erode important evolutionary legacies and reduce the adaptive potential of regional biotas. Reversing homogenization requires deliberate management interventions that specifically promote native species and resist the further spread of invasive generalists through urban habitats.

2.3 Environmental filters and stress gradients

The conceptual framework of environmental filtering, borrowed from community ecology and applied to urban systems by Shochat et al. (2006) and elaborated by subsequent workers, holds that the composition of urban biological communities reflects the outcome of a sequential filtering process in which regional species pools are progressively reduced by habitat loss, then by the physiological and behavioral requirements imposed by urban environmental conditions, and finally by biotic interactions among the remaining colonists. The principal urban environmental filters identified in the literature include impervious surface cover and its consequences for microclimate and hydrology; atmospheric and soil pollution; artificial light at night and acoustic noise; altered plant community composition, particularly the prevalence of exotic ornamentals; and the abundance of domestic predators, especially cats and rats, which impose intense predation pressure on ground-nesting birds and small mammals (Grimm et al., 2008; Faeth et al., 2011).

These filters do not operate independently; they interact in ways that produce city-specific combinations of stress gradients that are difficult to generalize across climatic zones. In arid-region cities of the Middle East and Central Asia, for example, the provision of irrigated green space substantially reduces thermal stress relative to surrounding desert landscapes and can actually support higher bird and arthropod densities than adjacent non-urban habitats (Ibrahimov et al., 2024; Bababayli et al., 2025). In contrast, in temperate European cities characterized by fragmented patch-matrix landscapes, habitat connectivity and patch size emerge as the dominant filters for forest-interior bird species and woodland invertebrates (Niemelä, 1999). These context dependencies underscore the importance of empirically testing ecological hypotheses within specific urban systems rather than assuming the universal transferability of findings from well-studied metropolitan areas.

3. GREEN INFRASTRUCTURE AND ECOSYSTEM SERVICES

3.1 Conceptual foundations

The concept of ecosystem services — the benefits that ecological systems provide to human societies — was systematized in the Millennium Ecosystem Assessment (2005), which classified services into four categories: provisioning (food, water, fiber), regulating (climate regulation, flood control, pollination), cultural (recreation, aesthetics, spiritual values), and supporting (nutrient cycling, primary production). The application of this framework to urban systems, pioneered by Bolund and Hunhammar (1999), revealed that even highly degraded urban green spaces provide economically significant regulating and cultural services, including stormwater retention, air-quality improvement, urban heat island mitigation, and recreational opportunities. Subsequent quantitative assessments have substantially extended and refined these initial estimates (Haase et al., 2014).

Green infrastructure represents the purposive planning and management of urban green elements — parks, urban forests, street trees, green roofs, permeable pavements, wetlands, and riparian corridors — as a spatially integrated system rather than as isolated amenities (Tzoulas et al., 2007). The critical distinction between conventional urban greening and green infrastructure lies in the explicit recognition of functional connectivity among green elements: a network of small, interconnected green patches can collectively provide more ecosystem services and support more diverse communities than the same total area of isolated, unconnected fragments (Elmqvist et al., 2013). This connectivity dimension has important implications for biodiversity conservation: it means that the spatial configuration of green elements, not merely their total area, determines the biological and functional outcomes of urban greening programs.

3.2 Biodiversity outcomes

Empirical evidence from a range of taxonomic groups confirms that well-designed urban green infrastructure can support significant biodiversity, particularly when green spaces include native plant species, structural heterogeneity, and limited management intensity (Lepczyk et al., 2017; Aronson et al., 2014). Urban parks of more than 10 ha have been shown to support forest-interior bird species that cannot survive in smaller fragments, while green roofs planted with diverse native substrate communities can sustain specialist invertebrate assemblages comparable in richness to brown-field sites that serve as secondary habitat for grassland insects (Niemelä et al., 2010). Riparian corridors function as critically important linear elements within the urban green infrastructure network, providing movement pathways for mammals, amphibians, and macroinvertebrates across otherwise impervious urban matrices, and connecting urban fragments with peri-urban and rural habitat reserves (Tzoulas et al., 2007; Bolund & Hunhammar, 1999).

The relationship between plant diversity in urban green spaces and the diversity of associated faunal groups is generally positive, consistent with the resource-concentration and habitat-structural hypotheses derived from natural-habitat ecology. Native plantings, in particular, tend to support substantially higher arthropod diversity and abundance than comparable exotic plantings, because they provide host plants for specialist herbivores, pollen and nectar resources for native pollinators, and prey items for predatory insects and insectivorous birds (Faeth et al., 2011). This finding has practical implications for urban planting policy: the ecological gains from replacing exotic ornamentals with native species in street trees, park planting schemes, and domestic gardens may substantially exceed what can be achieved through increases in green-space area alone.

3.3 Regulating services: Urban heat island, stormwater, and carbon

Urban trees and vegetation provide well-documented cooling effects through shading and evapotranspiration that collectively reduce mean summer temperatures by 0.5–2.0 °C relative to ungreened urban surfaces, with effects reaching up to 8 °C in immediate canopy shade (Tzoulas et al., 2007). The urban heat island effect imposes substantial health costs in temperate and tropical cities alike, and climate projections suggest that its intensity will increase under most emissions scenarios, making urban greening an increasingly important adaptation strategy. Modeling studies indicate that increasing canopy cover from 20 to 40 percent across typical European city blocks reduces peak daytime temperature by approximately 1.5 °C and reduces the frequency of heat-stress events for outdoor workers by 30–40 percent (Haase et al., 2014).

Green infrastructure also delivers significant hydrological services. Permeable surfaces, rain gardens, bioswales, and urban wetlands intercept, absorb, and delay the release of stormwater, reducing peak flow discharges and the frequency of combined sewer overflows. Estimates from North American and European cities indicate that comprehensive green stormwater infrastructure programs can reduce peak runoff volumes by 40–80 percent relative to conventional grey infrastructure, at substantially lower lifecycle costs (Bolund & Hunhammar, 1999). Urban vegetation also contributes to carbon sequestration: mature urban trees store on average 7.8 to 22 kg of carbon per tree per year depending on species, size, and management, and urban forests as a whole are estimated to sequester approximately 28 million tonnes of carbon per year globally, though this figure represents a small fraction of total urban emissions and should not be presented as a substitute for emissions reduction (Bolund & Hunhammar, 1999; Millennium Ecosystem Assessment, 2005).

3.4 Cultural and supporting services

The cultural services of urban green spaces — their contributions to human psychological well-being, social cohesion, and cultural identity — are among the most robustly documented yet most difficult to quantify in economic terms. Randomized experimental studies and longitudinal surveys consistently demonstrate that access to urban green space is associated with reduced psychological stress, lower rates of depression and anxiety, improved attentional capacity, and higher self-reported life satisfaction across diverse demographic groups (Tzoulas et al., 2007). These effects operate through multiple mechanisms including the restorative effects of natural environments, opportunities for physical activity, facilitation of social interactions, and exposure to natural soundscapes and wildlife. The cultural services of urban green infrastructure therefore contribute directly to public health outcomes, with implications for healthcare costs and workforce productivity that substantially augment the ecological and hydrological value commonly assigned to green spaces in cost–benefit analyses.

4. FRAMEWORKS FOR URBAN ECOLOGICAL PLANNING

4.1 Landscape ecology principles in urban systems

The application of landscape ecological principles to urban planning has substantially advanced the conceptual foundations of urban green infrastructure design (Pickett et al., 2001; Elmqvist et al., 2013). Patch-corridor-matrix theory, originally developed for natural landscapes, translates directly into design principles for urban green networks: large core green spaces reduce edge effects and support interior species, linear corridors connecting fragmented patches enable movement and gene flow, and the permeability of the urban matrix to the movements of target species determines the functional value of connectivity at the landscape scale. Connectivity analyses using circuit theory, least-cost path modeling, and individual-based simulation have been applied in numerous cities to identify priority linkages for green infrastructure investment and to evaluate the biodiversity co-benefits of alternative urban development scenarios (Niemelä, 1999; Lepczyk et al., 2017).

Nature-based solutions represent an evolution of the green infrastructure concept that more explicitly links ecological processes to the delivery of societal benefits (Elmqvist et al., 2013). By framing urban greening interventions as solutions to specific urban challenges — flood management, heat stress adaptation, public health improvement, social integration — the nature-based solutions paradigm has proven effective in mobilizing political support and investment for urban ecological programs that might not be prioritized on biodiversity grounds alone. The European Commission’s commitment to deploying nature-based solutions across 150 European cities, and analogous programs in China, Singapore, and Australia, reflect the growing mainstreaming of urban ecology principles in metropolitan governance.

4.2 Knowledge gaps and research priorities

Despite substantial progress, several critical knowledge gaps limit the capacity to translate urban ecological knowledge into effective planning practice. First, the long-term dynamics of urban biodiversity remain poorly characterized: most published studies span fewer than five years, and there is consequently limited understanding of successional trajectories in urban green spaces or of the resistance and resilience of urban communities to the climatic extremes projected under future scenarios (Shochat et al., 2006; Grimm et al., 2008). Second, the relationship between structural features of urban green infrastructure — patch size, connectivity, plant species composition, management intensity — and the delivery of specific ecosystem services has been examined far more thoroughly for birds and plants than for soil fauna, freshwater biota, and pollinators, all of which provide services of high urban relevance. Third, socio-ecological research that integrates the perceptions, behaviors, and governance capacities of urban residents and planning institutions remains underrepresented relative to purely biophysical investigations.

Future research should prioritize long-term monitoring of biodiversity and ecosystem service provision in explicitly manipulated green infrastructure experiments, multi-city comparative studies that enable context-specific generalizations across climatic and socioeconomic gradients, and the development of spatially explicit planning-support tools that allow urban planners to evaluate biodiversity and ecosystem service trade-offs across alternative development scenarios in real time. The growing availability of high-resolution satellite imagery, citizen science biodiversity data platforms, and machine-learning-based species distribution models provides the technical foundation for such research, but requires coordinated investment in standardized protocols, open data infrastructure, and interdisciplinary collaboration between ecologists, planners, and social scientists.

5. CONCLUSION

The relationship between urbanization and biodiversity is one of the defining ecological challenges of the twenty-first century. As cities grow to accommodate an additional 2.5 billion urban residents by 2050, the manner in which urban development is planned, designed, and governed will have irreversible consequences for biodiversity and for the ecosystem services on which billions of people depend. The evidence synthesized in this review demonstrates that urbanization imposes strong negative pressures on native biodiversity through habitat loss, fragmentation, environmental filtering, and biotic homogenization, but that these pressures are not uniformly severe nor, in all cases, irreversible. Strategic deployment of green infrastructure — grounded in landscape ecological principles, designed with native plant diversity, and managed to provide connectivity across the urban matrix — can substantially offset biodiversity losses and sustain the regulating, cultural, and supporting ecosystem services that cities require.

The critical insight emerging from two decades of empirical urban ecology is that the ecological quality of urban environments is determined not merely by the quantity of green space but by its configuration, composition, and management. Cities that invest in ecologically coherent green infrastructure networks, that prioritize native vegetation and habitat structural diversity, and that monitor and adaptively manage green space performance are demonstrably more successful in conserving urban biodiversity and delivering ecosystem services than cities that treat green spaces as aesthetic amenities rather than functional ecological systems (Elmqvist et al., 2013; Lepczyk et al., 2017). Translating this insight into practice requires sustained interdisciplinary collaboration between ecologists, urban planners, engineers, public health researchers, and communities, supported by appropriate governance frameworks and long-term investment in monitoring and adaptive management.

Urban ecology is no longer a peripheral subdiscipline: it addresses ecosystems in which the majority of humanity will live and on which the sustainability of the human enterprise increasingly depends. Future ecological research must engage directly with the complexity, dynamism, and social embeddedness of urban systems, deploying the full range of conceptual and methodological tools that modern ecology offers, while maintaining rigorous attention to the empirical foundations that give ecological knowledge its practical and policy relevance.

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