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LETTER TO THE EDITOR

Cosmopolitan conservation: the multi-scalar contributions of urban green infrastructure to biodiversity protection

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Abstract
Urbanization is a leading cause of biodiversity loss globally. Expanding cities alter regional ecological processes by consuming habitat and modifying biogeochemical and energetic flows. Densifying cities often lose valuable intra-urban green spaces. Despite these negative impacts, novel urban ecosystems can harbor high biodiversity and provide vital ecosystem services for urban residents. Recognizing the benefits of urban ecosystems, cities across the globe are increasingly planning for urban green infrastructure (UGI). UGI as a planning concept can transform how cities integrate biodiversity into urbanized landscapes at multiple scales and contribute to conservation goals. Full operationalization of UGI concepts can also reduce urban energy and resource demands via substituting polluting technologies by UGI, further contributing to the global conservation agenda. Realizing the potential contributions of UGI to local, regional, and global conservation goals requires addressing four inter-dependent challenges: (1) expanding social-ecological-systems thinking to include connections between complex social, ecological, and technological systems (SETS), (2) explicitly addressing multi-level governance challenges, (3) adapting SETS approaches to understand the contextual and biocultural factors shaping relationships between UGI and other causal processes in cities that shape biodiversity, and (4) operationalizing UGI systems through robust modeling and design approaches. By transforming UGI policy and research through SETS approaches to explicitly integrate biodiversity we can support global conservation challenges while improving human wellbeing in cities and beyond.

Keywords Conservation · Ecosystem services · Environmental governance · Urban green infrastructure · Urbanization

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Introduction

Biodiverse ecosystems and the ecosystem services they provide are vital for human well-being in multiple ways (MEA, 2005), especially in cities (McPhearson et al. 2022). Ongoing urban human population growth (United Nations 2019) will increase the importance of urban ecosystems and the services they provide, including maintaining and enhancing human ecological awareness (Shwartz et al. 2012). Urbanization is one of the leading causes of global biodiversity decline, often leading to permanent land-use changes as cities expand, and the loss of intra-urban green spaces as cities densify (Maxwell et al. 2016). Despite general trends of biotic homogenization in urban areas (Mckinney 2006), they also serve as novel ecosystems integral to the survival of many urban adapted species (e.g., *Apus apus*, *Passer domesticus*) - including rare and endangered species (Luna et al. 2018; McPhearson and Wijsman 2017). Urban ecosystems also modulate the global commodity flows required by urban industries and residents, such as raw materials, fuels, foodstuffs, and consumer goods (Weidner et al. 2019), impacts that are not directly perceived by most urban residents (Liu et al. 2003). Biodiverse urban ecosystems, as key components of urban green infrastructure (UGI) systems, directly and indirectly support biodiversity conservation goals from local to global scales. Expanding actionable research programs on biodiverse UGI, defined here as a living system integrating built and ecological systems to support social well-being and health (synthesized from Pauleit et al. 2019, Matsler et al. 2021, Grabowski et al. 2022), becomes a key tool for transforming urban and regional planning in support of global biodiversity conservation and meeting the Convention on Biological Diversity (CBD) 2050 goals. CBD goals include goal A of addressing ecological integrity and connectivity, goal B on the accessibility of nature's benefits to all, goal D, regarding the need to address financial and practical barriers to achieving the 2050 vision, and Action Target 14, aiming to fully integrate biodiversity values into multi-scalar and sectoral policies (Convention on Biological Diversity 2021). Here we address four linked areas for in support of advancing biodiverse UGI research and practice, namely, overcoming conceptual barriers in research and communication, addressing multi-scalar governance challenges, supporting contextual and inclusive applications, and developing city wide models and design tools.

Overcoming conceptual barriers with spatial social-ecological-technological systems approaches

Meeting the 2050 biodiversity goals and actions discussed will require understanding the multi-scalar and systemic contributions of UGI to biodiversity conservation (Fig. 1). Policy integration in turn requires how biodiverse UGI functions as a critical sub-system within urban social-ecological-technological systems (SETS - Grabowski et al. 2022; McPhearson et al. 2022; Keeler et al. 2019; Tratalos et al. 2007). This requires understanding and communicating to diverse stakeholders the value of biodiverse UGI for urban ecosystem services as moderated by SETS interactions (McPhearson et al. 2022), including the contributions of biodiversity to human health and wellbeing (Marselle et al. 2021), at multiple spatial scales. At the site level, building design, site features, and site management - including elements like bioswales, street trees, green roofs, domiciles for ecosystem engineers such as beavers, and facultative soil and hydrometeorological conditions - provide the 'building blocks' of habitat which can be directly influenced by management and designed decisions. While

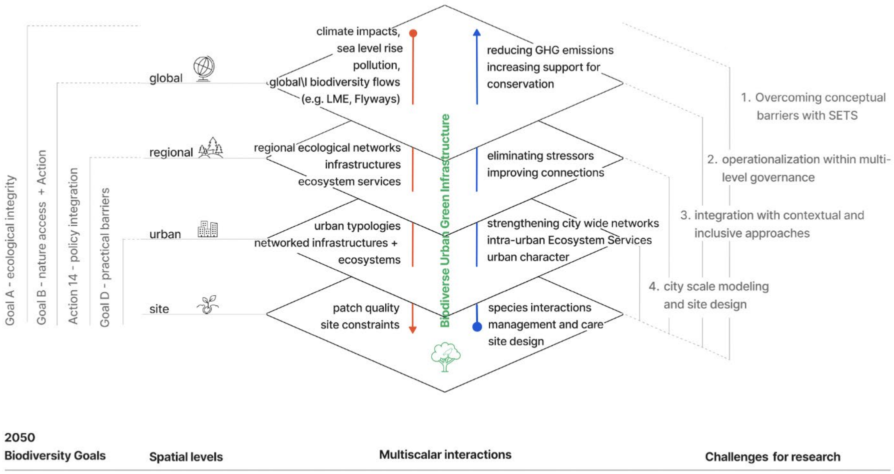

Fig. 1 Relationships between Biodiverse UGI and global, regional, urban, and site level drivers of biodiversity loss and gain in urban areas, interactions with the 2050 CBD biodiversity goals, and the four challenges of overcoming conceptual barriers with SETS, operationalizing biodiversity within the multi-scalar governance regimes of UGI, inclusively integrating biodiverse UGI in diverse contexts, and developing city scale modeling and site design tools

small, these engineered ecological elements are fundamental to UGI's ability to provide positive experiences with urban nature, reinforce environmental and place-based identities, provide a sense of quality, and improve environmental performance. However, site-level biodiversity is highly sensitive to local conditions - including pollutants such as heavy metals, biocides, road salt, runoff, and building materials (Huber et al. 2016, 2017; Galster and Helmreich 2022; Vega-Garcia et al. 2020), and intense variations in microclimate (Rizwan 2008). The qualities and characteristics of these networks spanning city boundaries determine the multiple functions and benefits that they provide, which can have positive feedbacks on site conditions for various taxa, and in turn reinforce the quality of citywide UGI (Lepczyk et al. 2017). Biodiverse UGI is also interdependent with regional biodiversity, for example, nearly half of all species found regionally in Germany can also be found in major cities (Sweet et al. 2022). Moreover, regional water quality issues and aquatic biodiversity declines often result from urban drainage and wastewater systems (Reid et al. 2019). This means that UGI modulates regional environmental processes, reducing or eliminating environmental stressors such as pollutants, and improving ecological connections, which in turn has positive feedbacks with regional species diversity and environmental baselines (Connop et al. 2016). However, social institutions and relationships across these spatial scales are complex, often fragmented, and influenced by built infrastructure systems. Other environmental-technological connections are truly global. Current rates of climate change will impose significant transformations upon cities, and cognizant of this, cities globally are attempting relatively rapid large scale green transformations. Since urban areas are the primary sources of GHGs, rapid transformation of urban systems by UGI and associated greening of energy, transportation, and manufacturing systems to dramatically reduce emissions, could buy significant time for even more effective adaptation, a potential win-win. While those transformations go beyond what we traditionally conceive of as urban green infrastructure, addressing UGI's relationships to those myriad infrastructures will be required to effectively design and plan for biodiverse UGI networks. UGI can also substitute for polluting technologies and lower the global demand for energy, resources, and intensive agricultural production, all reducing threats to biodiversity. Urban greening also taps into a deep human need for a healthy environment, and understanding and communicating the value of biodiverse UGI through SETS approaches can build social support for larger transformations of human-nature relationships.

Explicitly wrestling with multi-scalar governance challenges

Operationalizing biodiverse UGI within multi-sectoral policies and plans (CBD Action 14) requires explicitly addressing the challenges of multi-scalar governance. Existing social-ecological-systems approaches have long sought to understand the ideal fit between ecological systems and their governing social systems (Folke et al. 2007). Expanding to a SETS framework in cities requires understanding how many of the desired functions of UGI requires careful coordination and co-operation of individuals and urban institutions managing diverse infrastructures and aspects of urban life (Buijs et al. 2019, (McPhearson et al. 2022). The effectiveness of cities to engage in deliberate transformation hinges upon their ability to address complex multi-scalar governance problems in a timely manner.

Doing so presents several well documented challenges. Much of urban green space is privately owned and managed (or not) by individuals subject to diverse social pressures, municipal regulations, and enacting their preferences in accordance with their capacities, affordances, and cultural preferences. The biodiversity of these private lands is directly influenced by how municipally owned lands are managed and their relationship with regional ecosystems (Lepczyk et al. 2017). At the city scale, municipal policies coordinating and supporting the creation of city-wide GI networks can significantly improve biodiversity (Aronson et al. 2017). Keys for municipal and private adoption of biodiverse UGI appears to be demonstrated cost effectiveness, added value over grey infrastructure systems, alignment with ecological ethics and understanding, and political/regulatory expediency. Demonstrating the multiple benefits of managing for biodiversity can maximize alignment with other urban agendas to design for livable cities. Examples include managing municipal lands as biodiverse wildflower meadows and patches instead of frequently mown grass to reduce costs, runoff, and greenhouse gas emissions, while increasing the diversity and abundance of arthropod and bird species and communities (Proske et al. 2022); designing biodiverse green roofs for increased thermal insulation and stormwater retention functions (Kabisch et al. 2022); planting diverse street trees to reduce pests, disease, and maintenance costs (Dümpelmann 2019); UGI with structurally diverse vegetation increases thermal comfort and reduces building energy costs while increasing species diversity (Threlfall et al. 2017). Significant research also links numerous positive impacts of biodiversity on the health of urban inhabitants, though also calls for care in identifying negative relationships (Nazarian et al. 2022).

To maximize the functionality of biodiverse UGI systems, municipalities often engage in regional coordination and collaboration to create larger networks of lands integrated with infrastructure systems (Connop et al. 2016), including peri-urban agricultural and touristic areas (Rolf 2021), and very often, water supply, and recreational lands. These systems are the life support systems of cities, and yet across the world many urban residents have highly unequal access to them. Inequities in distribution requires addressing the role of power in urban planning and design processes, as well as the inherent difficulties of integrating UGI dense urban fabrics, often requiring creative and small-scale interventions like bioswales, urban gardens (Seitz et al. 2022), green facades and roofs, and smaller heterogeneous patches or ruderal spaces within the city (Kennedy 2022). SETS makes that supporting well-understood ecological processes, such as ecological connectivity between sites, patches, and corridors (Hardy et al. 2022), require integration into the planning and design standards of other infrastructure systems, such as transportation, streetscapes, and buildings, as well as regional parks, open space systems, and working landscapes. Identifying and aligning the functions and benefits of UGI with those of other infrastructure systems, targets CBD goal D: overcoming practical and financial barriers to biodiversity conservation.

A SETS approach is also useful to study how ecological self-organization fits within complex and mosaiced governance regimes. Cities have contained both carefully managed and designed elements, such as street trees, and many other urban-adapted species with both negative and positive effects on human wellbeing and health (Dunn 2018; Marselle et al. 2021). No matter how hard humans attempt to control urban ecosystems, nature finds a way to adapt and evolve, as evidenced by proliferation of aggressive invasive species worldwide, who are often the most robust species for disturbed and contaminated sites (Kowarik 2008; Padayachee et al. 2017). How self-organized ecosystems align or conflict with societies' desires for specific ecosystem service, and how society assigns uses to different parts of urban space, is a key research area. The ability of humans to shape urban nature to provide contextually relevant ecosystem services faces the additional challenge of understanding what species and functional traits can thrive in highly variable urban habitat conditions. Allowing for and learning from spontaneously arising urban nature is an obvious way forward on this question, however, may also create real or perceived ecological disservices such as providing habitat for species seen as noxious weeds, pests, or disease vectors (Marselle et al. 2021). These concerns are not limited to invasives, as many species selected for some aesthetic or functional traits may also create disservices and negative health impacts, like the emission of biogenic volatile organic compounds or allergenic pollen (Calfapietra et al. 2013). Some disservices, like perceived allergenicity, can be mediated by beneficial interactions with biodiversity, as in the multiple and poorly understood positive health effects of diverse microbiota on human health and inflammation response (Dunn 2018; Marselle et al. 2021). Other desired services, like water quality regulation and food production can also be negatively impacted by histories of contamination – turning ecological services into a health risk (Wortman and Lovell 2013). SETS makes clear that planning for biodiverse UGI must consider the balance of forces creating heterogeneous urban habitats while addressing multiple intersecting equity issues - including green gentrification – which emerge from complex interactions between UGI, social structures and technological infrastructures (Grabowski et al. 2023). The benefits provided by biodiverse UGI, and hence the support for integrating biodiversity into private lands across urban and regional GI regulations and policies, can be understood by examining theiur social, ecological, and technological contexts, creating another major focal area for research and policy.

Integration of biodiversity into UGI through inclusive and context sensitive approaches

Despite the recognized positive feedbacks between UGI and biodiversity at multiple scales 2050 (Fig. 1), a primary challenge creating biodiverse UGI systems is that urban environments are mostly designed for humans (Elmqvist et al. 2013; Lepczyk et al. 2017). This challenge is compounded by the lack of explicit research tying biodiversity to the desired functions and benefits of UGI in research, design, and maintenance (Connop et al. 2016; Apfelbeck et al. 2020). By explicitly considering biodiversity conservation as a goal of UGI systems, urban ecologists and conservationists can reframe the goals guiding the evolution of UGI as a part of interdependent and complex SETS infrastructures (Grabowski et al. 2017). Existing avenues to integrate biodiversity into urban planning and design practices, include landscaping, parks and open space planning, drainage systems (Parris et al. 2018; Kirk et al. 2021; Grabowski et al. 2022), and the integration of green elements into building envelopes as e.g., in ECOLOPES (Weisser et al. 2023) and Animal-Aided Design (Weisser and Hauck 2017). While there has always been broad support for some urban ecological elements, such as street trees (Dümpelmann 2019), support for biodiversity has waxed and waned in response to diverse development and urban planning pressures (Lachmund 2013). Given that intersecting mounting urban challenges are not only acknowledged, but experienced by billions of urban residents worldwide, we have a critical window of opportunity to place biodiversity as one of the pillars of sustainable and resilient urban agendas.

To do so, we must address the variability in human's perception of the value of urban biodiversity across cultures and sociological contexts (Linke 2020) and how this variability manifests in local regulatory contexts. For example, in Germany, bioswales standards include only a few taxa (DWA-A 138E 2005), a similar situation to mainstream green stormwater infrastructure design practices in the United States (Gill et al. 2020). Coming to a social agreement about a more 'uncontrolled' or 'messier' urban nature, likely requires extensive outreach and communication about the value of biodiversity, as well as embracing biocultural and Indigenous knowledge and governance (Hall et al. 2021; Tomateo 2021). Such an embrace requires a paradigm shift in our consideration of nature from "Nature for people" to "Nature and people" (Mace 2014), or one from permitted harm to relational well-being. This approach has long been practiced by practitioners of biocultural conservation (e.g., Rozzi et al. 2006), and has recently been promoted in urban areas (Elands et al. 2019). Combining systems (SETS) and biocultural approaches requires including the potential beneficiaries of UGI within design and planning processes to address distributional inequities (Grabowski et al. 2023; Well and Ludwig 2021).

Inclusively planning for biodiverse UGI also requires addressing the contextual meaning of biodiversity. Biodiversity itself can refer to the diversity and abundance of different taxa, ecological elements, as well as the genetic diversity of cultivars that have co-evolved in specific urban settings for cultural purposes (Görg 2004). This means that biodiverse UGI research and policy should address place-based ecosystem adaptation's reliance on local knowledge (Elands et al. 2019), the functional relations between ecological, taxonomic, and genetic diversity and desired ecosystem services (Kremer et al. 2016), and the need to integrate a contemporary understanding of microbiological diversity in UGI design and management (Watkins et al. 2020). This last point, of explicitly understanding the role of the microbiome in human health including how different types of UGI, building materials, and management practices influence microbiological diversity (Watkins et al. 2020), explodes most current conceptualizations of urban biodiversity relationships with human well-being. To operationalize such an understanding of feedbacks and relationships between biodiversity and UGI at different scales we must develop citywide modeling capacity in combination with site specific design tools.

Developing city scale modeling capability and site-based design tools

How society imagines and constructs knowledge around the feedbacks between larger global drivers of biodiversity loss and biodiverse UGI is currently the least understood (Fig. 1). In this sense, the idea of the living city and its relationship to biodiverse UGI must go beyond previous approaches for addressing urban resilience through urban ecological research (Pickett et al. 2004). We know that global climate change will have profound implications for urban ecosystems (Grimm et al. 2008). We also know our knowledge of past climate is insufficient to design systems that will function in future conditions (Kim et al. 2022) – and that we have historically not planned urban infrastructures well in relation to one another to address interdependent risks or synergize between planning, design, and maintenance (Grabowski et al. 2017). Some of these risks can be managed by harnessing complex feedbacks and interdependencies – e.g., integrating biodiverse Sustainable Urban Drainage Systems into streetscapes and parks to increases soil water availability to support vegetative health, especially in times of drought. Additionally, multi-layered vegetation may provide more resilience in the face of extreme wind events, as well as a greater heat mitigation effect, which in turn is fundamentally driven by relationships with building and street geometries, radiative balance, and microclimate (Rizwan et al. 2008). These complexities can likewise be addressed through the development of site-specific design strategies that can incorporate positive feedback in modelling how diversity influences functionality in specific contexts. Explicitly addressing the need for models of how biodiverse UGI affects urban SETS forms the basis for current research on urban ecosystem services (McPhearson et al. 2022), as well as the explicit research agenda of the Technical University of Munich's Research Training Group on Green Infrastructure (https://www.gs.tum.de/en/grk/urban-green-infrastructure/).

Conclusion: integrating biodiversity into UGI planning and policy as a key strategy to achieve the 2050 biodiversity targets

The overall challenge of understanding the systemic connections between diverse conservation strategies and and *global conservation targets*, is not unique to urban systems. A SETS perspective can be applied to understand the multi-scalar relationships between biodiversity, land use and management, infrastructure systems, social conditions, and governance in many contexts. It's application to understand Urban GI's contribution should proceed in collaboration with other multi-scalar, citizen science, and cross-sectoral monitoring and evaluation efforts to understand the impact of broader scale transformations in the human relationship with nature and socio-technical trajectories. Through comprehensive and collaborative evaluative efforts, coupled with system level understandings, models, and design tools will enable a continued transformation and adaptation of research and policy to study what approaches appear successful within their contexts.

UGI and SETS both point us towards a different paradigm of conservation, one in which humans and nature do not oppose one another, operate symbiotically with complex interdependencies subject to uncertainty. Within this paradigm, our goal is not to simply minimize and mitigate human impact, but to maximize the creation of positive relationships while managing our disruptive and destructive activities. Global urban demand for quality of life and improved human health in the face of rising challenges will largely be met by UGI. This transformative opportunity should be seized upon to bolster biodiversity within urban regions and simultaneously reduce negative global impacts of urban systems.

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Declarations

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