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Advancing Urban Ecology toward a Science of Cities

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Urban ecology is a field encompassing multiple disciplines and practical applications and has grown rapidly. However, the field is heterogeneous as a global inquiry with multiple theoretical and conceptual frameworks, variable research approaches, and a lack of coordination among multiple schools of thought and research foci. Here, we present an international consensus on how urban ecology can advance along multiple research directions. There is potential for the field to mature as a holistic, integrated science of urban systems. Such an integrated science could better inform decisionmakers who need increased understanding of complex relationships among social, ecological, economic, and built infrastructure systems. To advance the field requires conceptual synthesis, knowledge and data sharing, cross-city comparative research, new intellectual networks, and engagement with additional disciplines. We consider challenges and opportunities for understanding dynamics of urban systems. We suggest pathways for advancing urban ecology research to support the goals of improving urban sustainability and resilience, conserving urban biodiversity, and promoting human well-being on an urbanizing planet.

Keywords: urban ecology, conceptual frameworks, comparative research, urban systems, complexity

Despite significant challenges, cities are at the forefront of sustainability practice, serving as the focal points of actions promoting sustainability pathways (Rosenzweig et al. 2010). Ecological principles are key to transformative change to achieve resilience to climate change and other urban stressors (Royal Society 2014). How can scholars of urban ecology develop the necessary knowledge to promote resilience and help set cities and future urbanization on sustainable trajectories? What changes in the theory and practice of urban ecology can be envisioned to tackle such challenges?

In 2013, at the Society for Urban Ecology First World Congress in Berlin, we gathered a diverse, international team of leading urban ecologists to answer these questions. Rather than approaching these questions with a dense review, we developed a consensus to guide future urban ecological research. This hard-won consensus was achieved despite diverse perspectives, cultural traditions, and modes of application among our team. Our goals in presenting this consensus are to motivate new and advanced cross-city comparative ecology, to develop more unified conceptual frameworks to advance urban ecology theory, and to synthesize core urban ecology research principles to guide future research in the field.

Urban ecology has emerged as a multidisciplinary field with many of the tools needed for advancing cities' sustainability and resilience. Here, we define resilience as the capacity of a system to absorb stress, to continue to develop, and to change without a loss of essential structure, function, identity, and feedback (Folke 2008). We define sustainability as a continuing process of ensuring the balance of economic, environmental, and human well-being both now and in the future. However, the complexity of social–ecological interactions both within cities and across interconnected urban regions—where purportedly sustainable choices made in one place are not truly sustainable if they create social, economic, or environmental problems and trade-offs elsewhere—clearly represent "wicked" problems faced by today's urban ecologists. In this article, we discuss current findings, challenges, and opportunities to advance urban ecology toward a more holistic science of cities. We argue that central features of future urban ecological research should be synthesis, a complex-systems view, cross-city comparison at multiple scales, and inclusion of more disciplines that take advantage of emerging data sources, methods, and tools. We present a framework to jointly advance these features.

Urban challenges

The planet is rapidly urbanizing (figure 1), placing tremendous pressure on cities and urban areas to provide good living conditions for the majority of humanity. Accomplishing these fundamental goals in a way that ensures a resilient and equitable future for the human population and simultaneously maintains Earth's biodiversity and crucial

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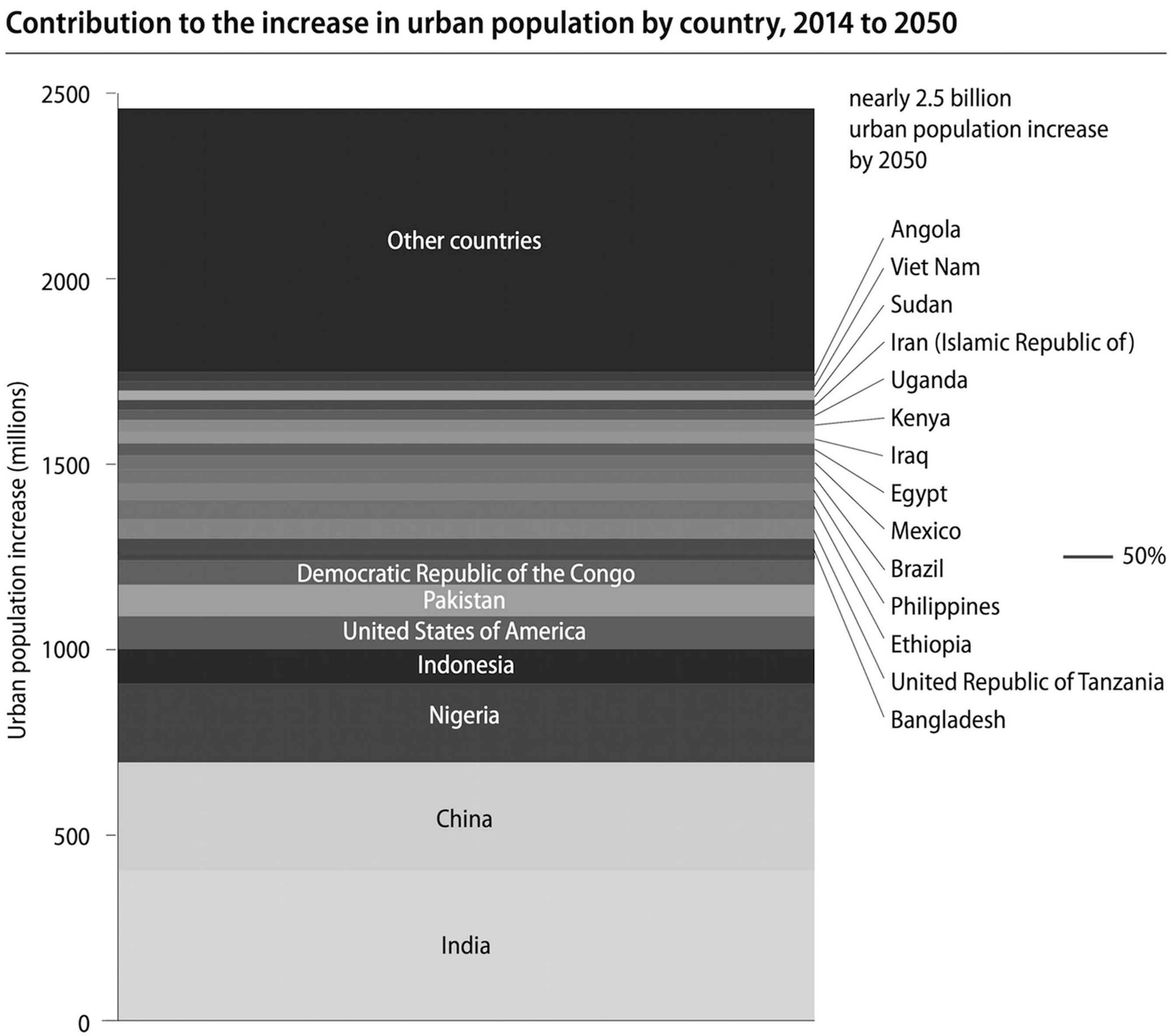

Figure 1. The countries shown are projected to contribute 25 million or more to the global urban increment between 2014 and 2050. The category "Other countries" includes countries with urban increments of less than 25 million each. India is projected to add 404 million urban dwellers, China 292 million, and Nigeria 212 million. The United States will continue to add significantly to its urban population, with nearly 90 million new urban inhabitants by 2050 (UN 2014).

ecological processes is essential to achieving a transition toward sustainability. For example, the Global Urbanization Prospects (UN 2014) found that urbanization is proceeding as expected with 54% of the world's population now living in urban areas. The world's current urban population of 3.9 billion is expected to surpass six billion by 2045 (UN 2014), putting services that urban ecosystems provide to residents at a premium (McPhearson et al. 2015). The amount of built infrastructure that will be deployed to develop new urban areas is dizzying (Ahern et al. 2014), and embodied within that infrastructure is a tremendous drain on natural resources from elsewhere. This massive demand for new infrastructure represents a key opportunity for using ecologically based design, architecture, and planning in development and governance processes.

Cities are under threat of climate change and associated extreme events, such as drought, catastrophic storms, storm surges, and heat waves (figure 2). Cities are also confronted with a mix of growing challenges from population growth that outpaces infrastructure development, growing slums and informal settlements, changing demographic characteristics, social inequality, economic fluctuations, pollution, local changes in climate and water systems, ageing infrastructure in need of replacement, and other stressors. These

Figure 2. Storm surge inundation and flooding in New York City following landfall of SuperStorm Sandy (2012). Sandy was not unprecedented, because storm surges of similar magnitude have been documented. However, social, ecological, and economic impacts were significant and spurred the city to establish a special task force, the Special Initiative for Recovery and Resiliency, for rebuilding and improving resilience in the city. Photograph: Allison Joyce/Getty Images.

factors interact dynamically, often in complex ways with each other and with climate change, to affect urban systems (Bettencourt et al. 2007, Grimm et al. 2008). Disturbances from migration, development, armed conflicts, epidemics, and economic upheaval are commonplace in urban systems. Planning, designing, and managing urban spaces across multiple scales require understanding how the many interacting components and subsystems together create patterns and processes that influence system dynamics. Urban decisionmakers—from mayors to neighborhood activists and from investors to corporate leaders—need tools and financial resources to navigate the transformation of their communities along sustainable pathways and to promote the resilience of desirable transformed states (Pickett et al. 2014, Childers et al. 2015).

For example, cities are increasingly looking to green infrastructure to meet demands for such benefits as urban air temperature cooling, stormwater absorption, drinking water supply, and improved human health (Elmqvist et al. 2013). Urban ecosystem services are the benefits urban residents derive from local and regional urban ecosystem functions (Gomez-Baggethun et al. 2013, Larondelle et al. 2014). However, ecosystem services are not simply a benefit of ecosystem functioning but rather are coproduced by people *and* ecosystems (Andersson et al. 2015), emphasizing the need for an integrated approach to understanding their production. Moreover, urban populations benefit from ecosystem processes occurring well beyond the boundaries of their cities, which yield ecosystem services from regional and even distant nonurban ecosystems. A social–ecological systems approach in urban ecology is crucial for understanding urban ecosystem services and managing ecosystems and green infrastructure to meet goals and needs of increasing and diverse urban populations in the context of urban change. In addition, managing and designing urban ecosystems to ensure the resilient and equitable supply of ecosystem services requires expert, local ecological knowledge (Faehnle et al. 2014) and often involves extensive built and technical infrastructure (Grimm et al. 2013). The importance of built infrastructure to the delivery of services in cities demonstrates the need for scholars of urban ecology to interact more with engineers, architects, and designers (Ahern et al. 2014). In addition, the importance of matching the supply of urban ecosystem services so that they are locally accessible to those who may benefit from them (McPhearson et al. 2013, Haase et al. 2014) stresses the need for urban ecology to interact more directly with the field of economics and sociology. This showcases the significance of linking human needs and actions with the structure and function of urban ecosystems—an approach developed uniquely within urban ecology (Niemelä 2014).

Figure 3. An example of urban ecology **in** *cities: New School research assistant Mu Hsiao Lan collecting vegetation and soil data in Marine Park, Brooklyn, as part of the MillionTreesNYC Afforestation Study (e.g., Falxa-Raymond et al. 2014). Photograph: Timon McPhearson.*

The global expansion of urban ecological research

Urban ecology has grown rapidly and expanded globally, in both research and practice, in the last two decades. Pioneered by investigators in Europe and Asia (Kowarik 2005, Sukopp 2008, Wu 2014), with this recent expansion, the field is poised to make further progress. For example, since the two US long-term ecological research (LTER) sites in Baltimore, Maryland (BES), and Phoenix, Arizona (CAP), were launched in 1997, over 1000 articles, books, and book chapters have been published, and over 130 students have been trained in urban ecology by these two research programs alone. Long-term urban ecological research in Seattle, New York, and other US cities has also contributed significantly to the theoretical and empirical basis of the field. Urban ecology research centers have now been established in other US cities (e.g., Minneapolis, Boston, Los Angeles) with increasing collaboration globally, especially with long-standing urban ecology research programs in European cities as well as with established or emerging programs in China, South Africa, and elsewhere across the world. The rapid growth and expansion of urban ecology globally has resulted in a heterogeneous and evolving field, with neither a firm, fixed disciplinary boundary nor a clear internal structure. Given the youth of the field, it is reasonable that it is still evolving and provides a unique opportunity for shaping future research (Niemelä 2014). Here, we consider how the field can mature.

Ecology *in*, *of*, and *for* cities

Ecology *in* cities research that uses ecological approaches from wild and rural ecosystems in analogous "green" patches within urban areas forms the early foundation and backbone of the field (Grimm et al. 2000, Sukopp et al. 2008). It also serves a significant role in expanding ecological expertise to inform urban biodiversity conservation, landscape design, and natural resource and wildlife management (Nilon 2009). For example, advising on how best to manage urban landscapes to meet multiple biodiversity and ecosystem service goals requires local ecological knowledge (figure 3). Similarly, understanding how climate change affects ecosystem structure, function, and services in cities requires a diverse set of expertise, which is increasingly being found within the expanding boundaries of urban ecology. Many of the changes in urban areas anticipate alterations driven by global environmental change (Grimm et al. 2008) and urban systems can serve as model systems for examining the interaction of social and biophysical patterns and processes (Collins et al. 2011).

Ecology *in* cities is classic urban ecology focusing on primary ecological questions in urban areas, such as how

Box 1. Key questions remaining to be addressed through ecology *in* cities research.

- How does ecological community structure affect ecosystem functioning in different habitat types?
- How do different levels of biodiversity, in different climates, and at multiple spatial scales affect ecological functioning and services?
- What is the role of nonnative species? How do they affect community dynamics, ecosystem structure and function, and biodiversity and ecosystem services?
- What biotic mechanisms, such as competition, predation, and parasitism, explain changes in biodiversity in cities, and how do they relate to human-assisted dispersal or management?
- What are the reciprocal relationships of soil and substrate heterogeneity and the structure of microbial and plant communities, and how does designed heterogeneity affect these relationships over the long term?
- How does microbial diversity affect nutrient cycling and patterns of biodiversity?
- How do nutrient dynamics, especially of nitrate and phosphorus, differ in differing urban contexts and in multiple habitat types? How do biogeochemical patterns and processes, including of pharmaceuticals and other contaminant materials, differ in various habitat types and urban contexts?
- How do urban plant traits differ from those of nonurban plants and affect plant performance and ecological resilience?
- How do the fragmentation and size of green spaces affect their biodiversity, regeneration, and ability to provide ecosystem services?
- What is the role of metapopulation dynamics for urban biodiversity, and how does this interact with human activities in urban ecosystems?
- How do urban environmental stresses and disturbances influence biogeochemical processes, plant productivity, soil respiration, and animal behavior and physiology?
- How are disturbance regimes and their impacts on urban ecological patterns and processes altered by people?

Note that the list is illustrative not comprehensive.

ecological patterns and processes in cities compare with those in other environments and how urbanization and development affect the ecology of organisms in urban habitats (McDonnell 2011). Any ecological topic is appropriate for study in urban ecosystems, whether behavioral, population, community, or ecosystem ecology. For example, understanding how urbanization affects biodiversity has been a long-term focus in urban ecology, with a growing canon of studies examining multiple taxa and their interactions (Shochat et al. 2006, Swan et al. 2011, Aronson et al. 2014). The fundamental question is how these patterns and processes differ compared with those in nonurban systems. Although ecology *in* cities has been interested primarily in biophysical dynamics of urban ecosystems, this area of research is increasingly examining how social structures, preferences, and organizations affect ecological dynamics in urban spaces (Groffman et al. 2014) through multidisciplinary collaborations (e.g., Pickett et al. 2001, Jenerette et al. 2011), with important research still left to do (box 1).

Ecology *of* cities incorporates ecology *in* cities (figure 4) but expands the reach of the ecosystem concept to assert that the city itself is an ecosystem (McDonnell and Pickett 1990, Grimm et al. 2000). The city as ecosystem explicitly incorporates humans as drivers of and responders to urban system dynamics along with nonhuman species and other system components (Grimm et al. 2000, Pickett et al. 2001, Cadenasso et al. 2006, Niemelä et al. 2011). Notably, the human component includes lifestyle and livelihood arrangements, formal and informal social institutions, and economic and political processes, among many other social attributes (Cadenasso et al. 2006, Boone and Fragkias 2012, Grimm et al. 2013).

Patterns and processes of urban systems in this view emerge out of the interactions and feedbacks between social and ecological components of those systems. However, the ecology *of* cities approach has developed in the last decade to increasingly incorporate built infrastructure into questions of how social and ecological components of urban systems interact (Cadenasso et al. 2006). Ecology *of* cities, then, is a systems science and integrates multiple disciplinary approaches—such as ecology and sociology—along with transdisciplinary perspectives—such as complexity, systems thinking, and sustainability—to study the city as a complex, highly interactive, social ecosystem (Alberti 2008). In this view, no single discipline is more important than another, but all provide approaches important to the study of cities as ecosystems. The novelty that urban ecology provides is the diversity of approaches among a broad set of disciplines that are beginning to inform our understanding of urban ecological processes, patterns, and heterogeneity (Grimm et al. 2000, Grimm et al. 2008, Childers et al. 2015).

However, there are challenges to achieving the promise of an integrated ecology *of* cities. Advancing such integration will require further expanding boundaries of the field to include still more disciplines (box 2). Integrating additional disciplines into the approach of cities as ecosystems is a key

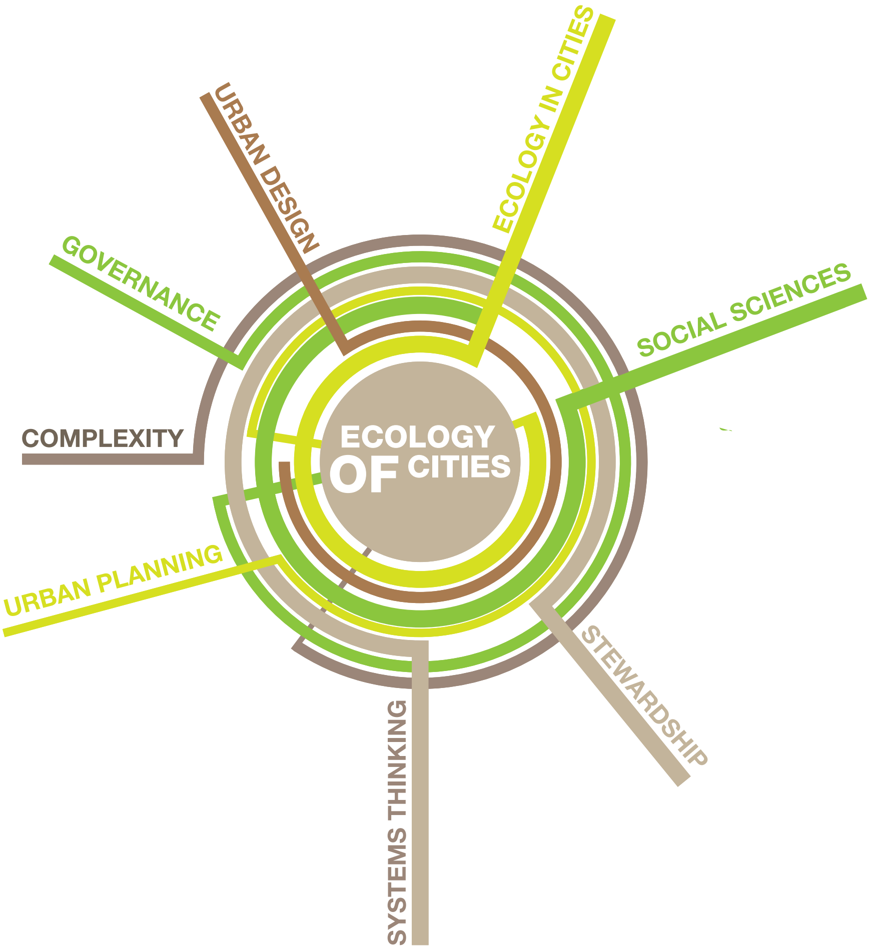

Figure 4. The ecology **of** ***cities approach incorporates ecology*** **in** ***cities, multiple disciplinary approaches and practices, transdisciplinary perspectives, and interactions with other ecosystems, which all are crucial to understanding the dynamics in complicated and complex urban systems.***

way to build a more holistic science of cities and one that can begin to move us from ecology *of* cities to ecology *for* cities (Childers et al. 2015). For example, an offshoot of civil engineering, industrial ecology, has been developing conceptual frameworks for cities in parallel with urban ecologists, but to date, there has been little interaction (e.g., Ramaswami et al. 2012). Central to industrial ecology's view of the city is the *urban metabolism* perspective, first proposed by Wolman (1965) as a city-as-organism metaphor that suggests modeling resources taken in and wastes expelled. The related concept of *ecological footprint* has gained traction as a heuristic tool for city planners. Both of these concepts focus on how concentrated human activity in urban systems affects and is affected by external resource pools. The ideas of industrial ecology share many similarities with some aspects of urban ecology and are worth integrating into a more comprehensive framework. Likewise, Ahern and colleagues (2014) illustrated how urban planning could become more interdisciplinary and inclusive through an experimental, ecological, "safe-to-fail" planning approach. In this approach, ecosystem services as an integrative concept is vital in guiding planning and in monitoring its success. This approach emphasizes that ecology *for* cities will require renewed focus on bringing research into various modes of practice, from urban planning, governance, and management to architecture, engineering, and design (figure 5). Thus, urban ecology is moving toward more transdisciplinary approaches. Such approaches not only depend on the interaction across academic disciplines and professional practices but also involve communities along with formal government agencies in decisionmaking. Consequently, the application of urban ecology is founded on a broad base of research interests but also seeks to engage affected communities and marry top-down and bottom-up civic processes.

We've distilled five general insights from urban ecology to guide future research. These normative statements, couched in terms of "must," reflect our shared consensus about the advances of basic and applied urban ecology. We find an urban ecological science *of* and *for* cities must meet the following five criteria: (1) It must be systems focused and therefore consider the relationships and feedbacks among social, ecological, and technical infrastructure components and subsystems of a specified urban system. (2) It must therefore be truly interdisciplinary and not embedded in any single disciplinary perspective or traditional conceptual frame, expanding to more explicitly include, for example, politics, technology, health, and governance. (3) It must be participatory, involving planners, managers, citizens, and other stakeholders to ensure the relevance of research and its implementation. (4) It must investigate multiple spatial and temporal scales, as well as cross-scale interactions. (5) It must advance new methods, models, and tools to deal with urban complexity in all its forms, incorporating new data (including "big data") and approaches from a diverse set of fields to integrate knowledge of urban system processes and dynamics.

The conceptual basis for synthesis in urban ecology

The diversity of conceptual approaches in urban ecology (Grimm et al. 2000, Pickett et al. 2001, Alberti et al. 2003, Grimm et al. 2008, Niemelä et al. 2011, Grimm et al. 2013) underlines the multiple, overlapping ways urban ecosystems are understood, studied, and theorized. Long-term studies in Berlin, Baltimore, and Phoenix have contributed

Box 2. Disciplines and theories integrated in urban ecological research.

- urban planning
- urban design
- architecture
- natural resource management
- economics
- sociology
- anthropology
- geography
- political ecology
- evolutionary biology
- landscape ecology
- community and ecosystem ecology
- urban and community forestry
- climate science
- hydrological science
- soil science
- environmental education
- transition theory
- resilience theory
- social–ecological systems theory
- complexity science
- sustainability science
- environmental science

Urban ecological research interacts with and incorporates knowledge and approaches from multiple disciplines and theories. To move toward a more comprehensive and holistic science of cities, urban ecologists will need to work more closely with many of the disciplines listed here and expand to others, such as engineering, health, industrial ecology, and political ecology.

enormously to theory development and conceptual advances in urban ecology. However, these studies are independent from each other and do not always share a common conceptual framework or methodology (McDonnell 2011, Wu 2014), although BES and CAP LTERs share underlying theoretical bases in hierarchical patch dynamics (Grimm et al. 2000).

Urban ecology has a rich roster of conceptual approaches, including, for example, social ecology, the human ecosystem framework, watershed studies, landscape ecology, and hierarchical patch dynamics (Cadenasso et al. 2006, McDonnell et al. 2011, Wu 2014, Niemelä 2014). Researchers have been building on these conceptual frameworks, borrowing freely from ecology, urban planning, and the social sciences, as well as creating new and unique conceptual frameworks such as ecotope analysis, urban–rural gradients, and urban scaling laws for guiding urban ecological research. Generally agreed on and widely used conceptual frameworks include the Human Ecosystem Framework guiding the BES (Pickett et al. 2001, Pickett et al. 2008), the urban social–ecological systems (SES) framework underpinning the CAP-LTER (Grimm et al. 2013), and the integrated human and ecological processes model (Alberti et al. 2003). Key features of these approaches include overlapping concepts integrated from multiple disciplines (box 2) and approaches (Zipperer et al. 2012). However, there is no unifying conceptual or methodological approach for investigating complex urban systems throughout the globe. Such a global synthesis is necessary to compensate for the fact that ecology *of* cities has different meanings in different contexts. Although a multiplicity of frameworks is necessary (Pickett et al. 2007), it will be important for conceptual and theoretical approaches to share common elements that take into account the diversity of social, ecological, cultural, economic, governance, and other contexts. The global diversity of conceptual approaches (McDonnell 2011) suggests the need for a more synthetic theory of cities and of urbanization to provide the theoretical and conceptual bases for research. Synthesis and clear statements of conceptual approaches in urban ecological research are therefore crucial for building comparative studies to create more generalized knowledge of urban systems.

The consensus of our diverse team about how to pursue synthesis can be summarized as normative recommendations presented earlier. An integrated science of cities will enhance, refine, and embrace existing conceptual frameworks. Ecological principles will be an important component and guide for such integration because ecology is preeminently a science of synthesis and interaction. Furthermore, ecology provides an open, systems-based, and hierarchical modeling strategy, which can facilitate the integration of diverse approaches and drivers (Pickett et al. 2007). However, the lack of conceptual integration and consequent divergence among specific models hampers comparability. With multiple conceptual frameworks in play, researchers develop studies differently in different cities, with results that are not easily comparable. For example, although urban ecological research has developed general indicators for services produced in urban ecosystems (Gomez-Bagethun et al. 2013), both the indicators and their calculations are derived from a wide variety of methods (Haase et al. 2014). The barriers to comparing ecosystem services across different urban contexts are shared with other cross-system efforts, such as sustainability indicators and mileposts, responses to climate extremes, and effects of design interventions.

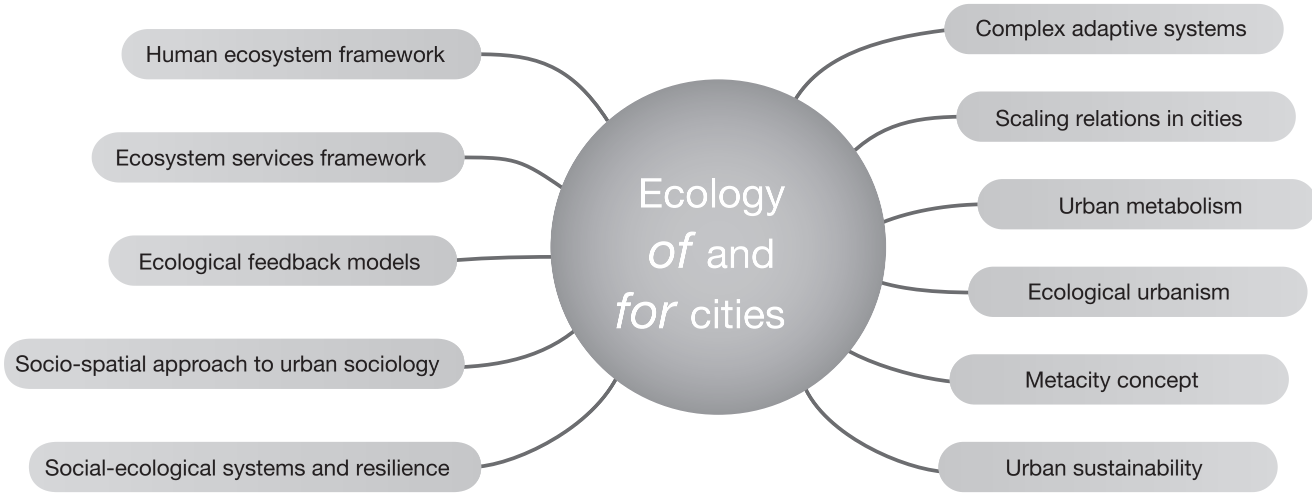

Figure 5. The key features of the ecology* of *and* for *cities approach includes the explicit recognition and incorporation of a historical trajectory of frameworks and synthetic approaches advanced in both urban ecology and other disciplines. We do not suggest that this illustration represents an exhaustive list of such approaches and frameworks for studying urban systems; rather, it simply points to conspicuous work being done in urban areas and how they are beginning to be linked and examined in an ecology* of *and* for *cities framework.

What will it take to achieve a more inclusive and more synthetic ecological theory of cities required to advance urban sustainability? Theory development and construction of models should go hand in hand with specific urban ecological research studies. We identify key elements required for conceptualizing cities as ecosystems (box 3), recognizing that ecology *in* and *of* cities approaches can employ different kinds of theory. In addition, diversity of theory may be required because conceptual frameworks must work across multiple spatial and temporal scales. The scale flexibility of conceptual frameworks is necessary because cities and urban regions occupy large, heterogeneous extents. Within the resulting mosaics, distinct patterns and processes may act at different grain sizes and extents and on varying time frames. In addition, frameworks must incorporate key, well-described drivers of urban system dynamics, including social and ecological processes (Pickett and Cadenasso 2009). This is because simplistic or region-specific models of urban change may tacitly neglect urban processes that act in different geographic regions or may not incorporate drivers such as teleconnections, consumption- and service-based growth, temporary or circular human migration, or the regionalization of urban processes emerging worldwide (McHale et al. 2015). Models must also identify plausible key relationships among components of the system because those relationships may not be stationary in time or space, requiring a comprehensive roster from which to construct place-specific or robust comparisons. In addition, emerging evidence of rapid biotic evolution in urban areas suggests the need to expand urban ecology to include studying the ecoevolutionary implications of urban-driven trait changes for those species that play a key role in ecosystem function and services (Alberti 2015).

Cities as complex adaptive systems

For building a science and ecological theory of cities, it is vital to recognize that urban systems can be truly complex (Batty 2008). Cities display emergent properties, have dynamics that are far from equilibrium, and require enormous amounts of energy to maintain themselves. Many urban systems display key properties of complex adaptive systems, meaning that they can be highly interconnected and unpredictable while having modular subsystems that confer redundancy and are capable of resiliency. Dealing with complexity in urban systems is challenging and will necessitate that urban ecology collaborate with and incorporate methods, tools, and approaches from complex adaptive systems science. Efforts to understand the complex nature of urban systems is still quite recent, but research on urban complex systems is providing an initial basis for describing some of the fundamental patterns of complex urban systems (Bettencourt et al. 2007, Batty 2008). For example, Bettencourt and colleagues (2007) described the nonlinear relationships of population size to urban growth, rates of innovation, and the pace of life in cities. Cities often display clear patterns of social inequality and have flows of resources and information that use system capacity in what appear to be barely sustainable but paradoxically resilient networks (Batty 2008). Developing methods and tools that can address the social, ecological, and technical infrastructure complexity of urban systems is key to advancing the goals of improving urban sustainability, livability, social equity, and resilience.

Box 3. Principles for conceptualizing urban systems.

- The structure of urban systems includes human and nonhuman organisms; abiotic components such as soil, water, land, climate, buildings, roads, and technological infrastructure; social institutions; politics and governance; and economic drivers—all of which interact to produce the observable functions of urban systems.
- Humans interact dynamically within social–ecological–technical/built system (SETS) components.
- Delineating boundaries and defining response units are crucial for empirical research, as is understanding the influences, material, and energy that cross boundaries.
- Urban ecosystem function emerges from the interactions, relationships, and feedbacks of system components.
- Urban systems are spatially heterogeneous and temporally dynamic.
- Linking urban system patterns with processes at multiple scales is a primary focus.
- Conceptual frameworks must work across multiple spatial and temporal scales.
- Conceptual frameworks must incorporate key, well-described drivers of urban system dynamics, including social, ecological, political, economic, and technical processes.
- The relationship among urban form, heterogeneous spatial structure, and system functions must be known to theorize and measure ecosystem services.
- Conceptual frameworks must be designed to enable comparative studies across cities

Urban form, structure, and functioning

Urban form—the spatial patterns of the built, infrastructural, and embedded biotic components of cities—is a crucial component of urban structure. An ecology *of* cities that seeks to describe relationships between urban form, structure, and functioning and rate of change will need to develop models, tools, and data sets that better incorporate interactions among the social, ecological, and infrastructure components of urban systems (McGrath and Pickett 2011). Linking urban form and structure to functioning could provide a novel starting point for examining urban system patterns and processes and generate a unique platform on which to build cross-city comparative research. Defining urban structure and key relationships between urban structure and ecological processes is challenging in landscapes characterized by dense and patchy spatial patterns (Pickett and Cadenasso 2009, Zhang et al. 2013).

In order to trace the spatial and temporal patterns of urban landscape structure, compare patterns across cities, or inform urban design and planning principles, we need to better understand the extent and variability of the relationships between urban landscape structures and their functions, such as urban heat (Larondelle et al. 2014, Hamstead et al. 2015). A spatially explicit understanding of how urban structures that relate to functions are distributed across an urban extent can enable planners and policymakers to better identify areas of vulnerability and spatially prioritize interventions. An example of recent advances includes a simple and reproducible approach for classifying the structure of urban landscapes (STURLA) that uses heterogeneous, composite classes that represent combinations of built and natural features and examine the response of a landscape function–surface temperature (Hamstead et al. 2015).

Climate and weather related extreme events such as heat waves can be exacerbated by the built environment. Heat waves in particular can lead to higher rates of mortality than all other natural disasters combined (Klinenberg 2002). A variety of social processes contribute to vulnerability to heat, including variation in social capital and legacies of disinvestment, which can affect vulnerability to heat waves. Furthermore, differences in intraurban surface temperature can be as large or larger than urban–rural temperature differences, and a number of social–ecological–technical infrastructure interactions have been found to determine climate outcomes in cities (Jenerette et al. 2011). For instance, the dense distribution of tall buildings influences the spatial pattern of solar radiation intensity and duration and so influences air temperatures. The highly heterogeneous distribution of vegetation in cities is a primary determinant of heat exposure, which is often greater for poor, elderly, and minority segments of the population, who are often less able to cope (Jenerette et al. 2011, Boone and Fragkias 2012). By similarly empirically linking urban ecological function to urban form and structure, researchers can improve the ability to conduct urban ecosystem services assessment, provide a rationale for holistic and integrative approaches to urban planning, and support urban design interventions to build resilience to climate-driven extreme events (box 4).

From social–ecological to social–ecological–technical systems (SETS)

Despite early articulations of the importance of built infrastructure in conceptual frameworks for urban systems

Box 4. Tree cover: Social–ecological integration.

Trees play many roles in urban ecosystems. We give an example of the relationship of tree canopy and the occurrence of crime (Troy et al. 2012). This is not only a description of the biophysical structure of an urban system but also a spatial analysis of social data and a case of social inequity.

Tree canopy is related to violent crime, including robbery, burglary, theft, and shootings. However, the relationship is negative, in contrast to the common assumption that trees hide criminals, contraband, or illegal activities. A 10% increase in tree canopy in neighborhoods ranging across Baltimore City and Baltimore County was associated with a 12% decrease in crime. Crime negatively correlated with tree canopy cover, even when controlling for social and economic variables such as income, age of housing, status as rural, race, type of housing, length of tenure, and amount of either agricultural or protected land in a neighborhood. The effect is greater for tree cover on public lands, suggesting that tree planting on public lands would better reduce crime than plantings on private land (figure 6).

Figure 6. Tree canopy cover (dark green), contrasted with grass (light green), buildings (grey), streets (black), and paved surfaces (yellow), in a neighborhood in west Baltimore, Maryland.

Furthermore, spatial analysis suggests that tree planting on public land other than rights of way will be more effective. The few neighborhoods in which tree canopy cover was associated with increased crime are characterized by contact zones between residential and abandoned industrial parcels. This finding suggests that relatively low neighborhood surveillance in such situations may permit crime to persist. Such situations may also exhibit relatively lower-statured, early successional vegetation that may in fact conceal illicit activity, in contrast to more mature tree canopies with open understories elsewhere. The example illustrates the social–ecological approach, and because tree canopy cover is often a historical legacy of previous occupancy or practices in a neighborhood, it also reflects social inequity in neighborhood canopy amenities.

(Pickett et al. 2001, Alberti 2008) and its explicit articulation in the Human Ecosystem Concept (Cadenasso et al. 2006), most urban ecology research primarily focuses on linking social science with biophysical science. We argue that urban ecology must move beyond a social–ecological conceptual framing to more explicitly address the social–ecological–technical/built system (SETS). The urban SETS framing is a systems approach that emphasizes the importance of technology in urban built infrastructure (Grimm et al. 2016).

In cities, built and technical infrastructure is often viewed as the most important line of defense against hazards and disasters. In much of the developed world, however, urban infrastructure is aging and proving inadequate for protecting city populations (for the United States, see ASCE 2013). And in much of the developing, rapidly urbanizing world, new infrastructure is being constructed at breathtaking pace, often without the benefit of ecologically based design (McHale et al. 2015). Traditional risk-avoiding engineering designs for infrastructure design focus on hard, resistant elements such as increased-diameter sewage pipes for stormwater management or tanks to store sewage. In contrast, more flexible, diverse, and ecologically based elements (Felson et al. 2013) include green infrastructure such as parks, permeable pavement, swales or retention basins, or agricultural and vacant land sites in urban areas (McPhearson et al. 2013). Urban infrastructure therefore mediates the relationships between human activities and ecosystem processes and may exacerbate or mitigate human impact depending on how it is developed.

Urban systems are undergoing multiple kinds of changes, from densifying and expanding cities (UN 2014) to others that are shrinking with de-industrialization followed by de-densification and land abandonment (Kabisch and Haase 2013, Haase et al. 2014). Insights from urban ecology are often overlooked in engineering, planning, and policy for any sort of urban future. We need to rethink what makes both grey and green built infrastructures—as well as human communities with their social, ecological, and technological couplings—resilient to environmental hazards, climate extremes, and shrinkage. Exploring the interactions among multiple infrastructures in urban systems using the SETS framework allows equal emphasis on the coupling of social, ecological, and technological dynamics and may help to identify the barriers to and opportunities for urban sustainability transitions.

If urban ecological research is to provide insight beyond ecology *in* cities for urban decisionmakers, then it will need to increasingly collaborate with engineers, designers, architects, planners, and industrial ecologists who work directly on the built environment to facilitate understanding of how both green and grey infrastructure can be linked—and in the future, deeply integrated—to deal with urban challenges and meet the needs of urban residents.

For example, in Baltimore, projects involving greening, the installation of curbside swales, the retrofitting of sanitary sewer lines, increased street-sweeping frequency, and the planting of desirable vegetation in vacant lots combine the insights of many disciplines and sectors. The efforts of ecologists, the city Office of Sustainability, the Department of Public Works, transportation engineers, community activists, and environmentally and socially motivated nongovernmental organizations combine in an effort to improve stormwater management, mitigate urban microclimate, reduce water contamination and heating, enhance neighborhood social cohesion, and boost human well-being. Social–ecological systems approaches have been successful at bringing the social sciences and ecological sciences together, and not just in urban systems (Grove et al. 2006, Collins et al. 2011). However, the technical and built aspects of cities are central to the very fabric of urban systems and, perhaps unintentionally, are often overlooked or ignored in social–ecological studies. An explicit SETS framing could invigorate the integration of built and other infrastructure approaches into urban ecology and help to build a more inclusive urban science that takes into account key needs and priorities from multiple interacting disciplines, practitioners, stakeholders, and ways of knowing.

A comparative research program for urban ecology

Despite major progress in the field, urban ecology has still not been able to elucidate general properties and dynamics of urban systems. For example, to generalize the potential benefits of street trees for improving urban air quality or public health (Weber and Medhi 2013, Nowak et al. 2014), cross-system comparisons are required. Furthermore, whether the assumptions of the models used to calculate such benefits are themselves complete, robust, and generalizable need to be tested and validated (Pataki et al. 2011). Therefore, to discover what is generalizable about urban systems and what is not, we need to develop a cross-city comparative research program to advance the ability to provide general knowledge on the nature of urban system patterns and processes (Niemelä et al. 2011, Breuste et al. 2013).

So far, urban ecology has predominantly focused on the ecology *of* and *in* specific cities and towns (McDonnell and Hahs 2009). This place-based approach is the basis for early and ongoing progress in developing a more nuanced understanding of ecological structure and function relationships within urban areas. However, if urban ecological research is to successfully inform decisionmakers on how to best preserve urban biodiversity, improve ecological and urban functioning, and provide sustained delivery of ecosystem services, we need to use the expanding canon of local studies more effectively to uncover general principles and guide decisionmakers (Niemelä 2014). Some comparative research has already started to make progress in this area (Niemelä et al. 2011, Seto et al. 2012, Aronson et al. 2014, Larondelle et al. 2014).

We expect local context, dynamics, and history to be strong predictors of patterns and processes within individual cities and urban areas (Niemelä 2014, McHale et al. 2015), but we also expect that some principles may generally apply to all urban systems or to a subset or type of urban systems. Comparing the ecology of multiple cities and urban areas can elucidate generalizations (McDonnell and Hahs 2009) but will require developing an urban ecological research agenda that considers multiple cities and regions. Comparative approaches must be bound by common denominators, such as the biophysical, social, and/or historical commonalities of regions. It will be helpful to evaluate the existing typologies of urban systems (e.g., Knox 2014) to guide the process of setting up research for a comparative ecology *of* cities, although we recognize that the field can mature from multiple kinds of comparative research. A novel synthesis of existing typologies may provide a starting point. Key aspects of the typology selected could include history, culture, demography, governance, dominant economy, spatial extent, geographic and biome context, age, urban form, growth rate, average income, biodiversity, hydrology, and biogeochemistry.

Complexity theory highlights the potential of gaining insight into general properties of cities that can serve as a starting point to investigate the underlining mechanisms. One pathway is to create new opportunities and platforms for sharing and linking existing data sets across multiple kinds of urban systems. Recent global urban biodiversity studies, for example, have provided a compelling starting point for this type of research (Aronson et al. 2014). In addition, accounting for the complexity, connectedness, diffuseness, and diversity of urban systems (McHale et al. 2015) can allow for the development and testing of global generalizations and, at the same time, encourage place-specific relevance of urban ecological research.

To advance urban ecology, we envision an integrated, interdisciplinary science grounded in multicity comparative research programs that use a unified conceptual framework, use similar investigative methods, and ask similar questions (Niemelä et al. 2014, Childers et al 2015). Shared research methodologies addressing similar research questions could be applied to multiple urban areas.

Long-term research and big data

Urban ecology has benefited enormously from long-term ecological research in urban areas. However, so far such research has been undertaken primarily in already developed—but manifestly not static—western cities. Long-term urban ecological research in other urban contexts, other biomes, and other sociocultural contexts could provide needed insight into the differences and similarities across the ecology *of* cities (Niemelä et al. 2014, McHale et al. 2015). Long-term research can expose decadal to century-scale processes, but it also can deal with faster temporal scales. Cities shrink, expand, and undergo rapid geographical and demographic change (McGrath and Pickett 2011). Still, urban areas highlight the flexibility of long-term research, which can extend to fine time intervals to capture rapid changes typical of urban environments. For example, the decadal US Census is too coarse temporally to capture many social, demographic, and economic changes in urban areas. However, focused social surveys, other administrative records such as tax and real estate information, and dasymetric mapping techniques can compensate for some shortcomings of the census (Grove et al. 2013). Land use also changes quickly in cities, so what once was a backyard lawn could within a short period of time become a garden, parking lot, or building. It will be important to articulate the significance of setting up long-term research in urban regions in constant or rapid flux over space and time. The changes in urban land mosaics present a challenge for effective long-term sampling regimes, especially those aimed at discovering the relationship of urban social–ecological structure to ecosystem functioning.

Responsibly using new forms of data, including “big data,” has the potential to generate new hypotheses and develop new methods for long-term urban ecological investigation. For example, data sets being generated through social media could help scientists understand how people use and perceive ecological and other spaces in the city. Wood and colleagues (2013) used social media data through flickr.com, a widely used online photo-sharing website, to understand when and where people use national parks. Wood and colleagues (2013) were able to demonstrate that crowd-sourced information can serve as a reliable proxy for more traditional empirical social surveys. This and similar social media analyses (Keeler et al. 2015) offer the opportunity to complement existing social science approaches to collecting information on urban resident activity in and around the city, including their location, behavior, and emotions or feeling about particular places. Big data can also emerge from municipal hotlines, utility use and repair records, planting and maintenance records of city arborists, crime statistics, and more. “CitiStat” programs, pioneered in Baltimore, with their emphasis on gathering and using data about city environment and agency performance, are spreading (*http://web.pdx.edu/~stipakb/download/PerfMeasures/CitiStatPerformanceStrategy.pdf*), and the emergence of Smart Cities and increasing use of sensors promise that the utility of big data for understanding urban systems will only increase with time (Knox 2014).

The emergence of multiple forms of big data creates exciting alternatives to assess how people use and respond to urban nature. New forms of data may be a crucial resource in examining the use, value, and social equity in access of particular spaces in the city, such as the parks, vacant areas, and nonpark open spaces that provide local benefits for human well-being. Moving beyond expensive and limited spatial and temporal coverage of social surveys by innovating use of social-media data, for example, could revolutionize social–ecological systems research and provide long-term data sets. Working with big data offers opportunities with multiyear to decadal data sets to understand human–nature interactions in the city as never before and could prove crucial to developing indicators and assessing progress on UN Sustainable Development Goal 11 (the “urban” SDG). However, research in this area is still emerging, with research questions and methods still varying widely. Initial correlation studies will be an important first step, but incorporating these data into modeling and scenarios has the potential for providing much needed insight into how to design desired urban futures for urban planners, designers, and managers. Furthermore, although many of these novel approaches (Hamstead et al. 2015) and data sources (Keeler et al. 2015) hold great promise, researchers must ensure that they are not perpetuating biases in terms of social groups that are represented by such novel data streams and that the data remain open and accessible to all. In other words, responsible governance is needed to handle big data.

Paths forward for urban ecology

How can we both honor the heterogeneity and complexity of urban systems and research traditions and develop an ecological science of cities that can yield general insights?

Urban ecology has made substantial progress by studying ecology *in* cities. The ecology of parks, yards, and even waste places has yielded great insights into urban biodiversity and ecosystem processes. Urban scholars have studied the individual components of urban ecosystems, uncovering key relationships, making predictions, and building the scientific understanding of how organisms in cities respond to the processes of urbanization and the unique aspects of urban environments. Evolution and acclimation of urban organisms are therefore now better and better known, but there are still significant gaps (Alberti 2015). During the last two decades, a new ecology *of* cities has integrated ecological research in cities with multiple disciplinary approaches, perspectives, and data to understand cities as dynamic, highly connected and interactive, human-dominated ecosystems. This new integration has brought ecology out of the distinct green spaces of the ecology *in* cities and has begun to explore the ecological functions of all components of urban form. However, there remains a host of critical ecological questions that need to be answered and empirical data that need to be gathered to understand the dynamics and process of cities as social–ecological–technical systems.

This missing empirical ecological knowledge may be the most significant limitation to building a more holistic science of cities. For example, we still know little about how the supply and demand of biodiversity, ecosystem function, and ecosystem services are related in urban environments and, indeed, how ecosystem services can be defined in cities, with their preponderance of technological structure (Grimm et al. 2016). We lack field data to address the urgent needs of city planners, policymakers, and managers that require scaling up from plot-based urban ecological research (Grove et al. 2013). The development of a cross-comparative research program, at both national and international scales, could provide the needed impetus for fueling research on both ecology *in* and *of* cities. Educating and training the next generation of urban ecologists in ways that provide the required disciplinary expertise to address complex societal questions—but also further development of a theory and science of cities—may be among the most important accomplishments the field can make.

Conclusions

The centrality of urban challenges and opportunities integrated with, driving, and responding to planetary change forces us to rethink the roles of cities in ecology. It challenges urban ecology and perhaps the field of ecology in its entirety to more fully integrate humans, their habits, attitudes, and technologies into conceptual frameworks and empirical research. We suggest that empirical and conceptual advances within urban ecology, as well as the diversity and increasing size of the field, have created the potential to transform urban ecology into a robust, more holistic science of cities, which may be more important now given the rapid urbanization of the planet. The goal is to develop scientifically rigorous understanding of urban systems at multiple scales to inform more ecologically sensitive urban planning, design, management, and governance toward cities and urbanization processes that are more sustainable, equitable, livable, and resilient to global change. Urban designers have approached this view as well (McGrath et al. 2007, Felson et al. 2013). Potentially, one of the reasons that designers and ecologists can interact effectively is because they are both thinking about a "synthetic" discipline. Ecology and design are well poised as a nexus for promulgating and promoting the effective use of a theory and science of urban systems. However, to advance that science will require motivated interdisciplinary urban systems scholars but also new networks, knowledge and data sharing, greater synthesis within the field and across disciplines, and cross-city comparative research that leverages the diversity and scholarship toward a more synthetic, consilient understanding of urban system dynamics.

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