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# Moving Towards a New Urban Systems Science

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## Abstract

Research on urban ecosystems rapidly expanded in the 1990s and is now a central topic in ecosystem science. In this paper, we argue that there are two critical challenges for ecosystem science that are rooted in urban ecosystems: (1) predicting or explaining the assembly and function of novel communities and ecosystems under altered environmental conditions and (2) refining understanding of humans as components of ecosystems in the context of integrated social-ecological systems. We assert that these challenges are also linchpins in the further development of sustainability science and argue that there is a strong need for a new initiative in urban systems science to address these challenges and catalyze the next wave of fundamental advances in ecosystem science, and more broadly in interdisciplinary and transdisciplinary science.

**Key words:** community assembly; ecosystem function; evolution; social science; sustainability; urban.

## Introduction

Ecosystem-scale research on urban ecosystems has expanded rapidly since the 1990s (McDonnell and Pickett 1993; Alberti and others 2003) and is now a widely accepted component of ecosystem science (Weathers and others 2016). This emergence was driven by the recognition that urban, suburban,

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and exurban ecosystems are increasingly where people are living, consuming resources, and producing waste. Urban ecosystems thus have distinct ecological characteristics and important environmental impacts (Grimm and others 2008a, b); and they provide unique and powerful opportunities for basic science advances in ecosystem science (Pickett and others 2011; McPhearson and others 2016). More practically, bringing ecological approaches to challenges associated with urbanization can point towards solutions to some of the most pressing problems in environmental science (Childers and others 2014).

After 25 years of research in urban ecology, we face exciting but challenging opportunities in this discipline. In particular, there are two critical challenges for ecosystem science that are rooted in urban ecosystems: (1) understanding the assembly and function of novel ecological communities and ecosystems under novel environmental conditions and (2) refining understanding of humans as components of ecosystems to create a deeper and more useful understanding of human–environment interactions in the context of integrated social-ecological systems. These challenges are linchpins in the further development of sustainability science, a problem-driven interdisciplinary field dealing with the interactions between human and environmental systems that link knowledge to action to advance the development of social-ecological systems that are ecologically sound, socially equitable, and economically viable (Matson and others 2016). There is a strong need for new initiatives in urban systems science to address these challenges and catalyze the next wave of fundamental advances in ecosystem and environmental science.

## The ''Communities of Tomorrow'' Are Being Assembled Today at an Urban Location Near You

Much of the early work on urban ecosystems was driven by the idea that urban environmental conditions, with elevated temperatures, atmospheric $CO_2$ levels, nitrogen (N) deposition and pollutants (for example, ozone, heavy metals), dramatically altered water balances, invasive species introductions, and rapid timescales of transition, were a useful analog for future environmental conditions. Early studies along urban to rural gradients addressed these factors (McDonnell and Pickett 1990; Pouyat and McDonnell 1991; Pouyat and others 1995) and also provided a platform for larger-scale urban ''footprint'' analyses (Luck and others 2001) and for whole-city flux analyses (Boyden and others 1981; Baker and others 2001) that broadened the focus of urban ecosystems research to include consequences of a city's resource use for regional to global processes.

However, interpreting results from urban gradient studies is complicated by the multiple factors that covary along these gradients (McDonnell and Hahs 2008). Further, concerns about the large number of natural and human factors influencing ecosystem processes and biotic community assembly along such gradients hindered extrapolation to broader areas of natural and semi-natural ecosystems. Now, an improved ability to parse diverse factors affecting community assembly (Swan and others 2011; Knapp and others 2012) and the emergence of ''novel'' communities and ecosystems in many places, that is, assemblages of organisms and environmental conditions that have not necessarily evolved and assembled in the absence of human action over long periods of time (Hobbs and others 2014) has rekindled interest in using urban areas as sentinels of ecosystem response to global change. The functions of novel ecosystems are unknown in many respects and addressing this gap is a frontier challenge in ecosystem science over the next 20–50 years.

The presence of novel ecosystems in urban areas thus represents an excellent opportunity to study the assembly of novel communities and ecosystem function under environmental conditions representative of and/or relevant to the new climates emerging due to global climate change. It is not clear if the often hyper-diverse mixtures of cultivated and spontaneously establishing species that include escaped cultivars, introduced weeds, and remnant or naturally establishing native species will function similarly to the ecosystems that urban systems have largely replaced. Moreover, there is high potential for these novel ecosystems to spread into surrounding non-urban regions and to influence the composition, diversity, and evolution of the continental flora and its ecosystem functions (Johnson and others 2015; McDonnell and Hahs 2015). Indeed, it is likely that areas at the ''wildland-(ex)urban interface'' with agricultural and less human-dominated ecosystems (Radeloff and others 2005) are where the communities and ecosystems that will dominate the continent over the next 100 years are being assembled. Critically, the linkage of biodiversity and community structure with ecosystem function and services is even more uncertain in urban areas than in natural areas, due to their novel composition and environment. Hence, a focus on novel ecosystem assemblage, its drivers, and its consequences should facilitate fundamental advances in our ability to understand and predict the structure and function of ecosystems in a rapidly changing world.

In addition to terrestrial environments, urban areas also provide analogs—even harbingers—for aquatic ecosystems of the future. The widespread ''urban stream syndrome'' that derives from the physical degradation of urban stream channels due to increased high flows (Walsh and others 2005) involves changes in nutrient loads and the presence of a wide range of pharmaceutical compounds used by humans (Kolpin and others 2002) that affect both the structure and function of stream communities (Rosi-Marshall and Royer 2012; Drury and others 2013; Rosi-Marshall and others 2013). Just as in early studies of urban terrestrial ecosystems, the complexity of the physical, chemical, and biological changes associated with the urban stream syndrome have complicated interpretation of results from urban stream studies in the context of broad aquatic ecosystem response to global environmental change. However, improved approaches to community analysis suggest that the prospects for isolating specific effects and making interpretations relevant to whole ecosystem structure over broad areas are promising (Clark and others 2001; Carpenter and others 2009; Scheffer and others 2009; Dodds and others 2010).

The research agenda that can emerge from using urban areas as analogs for the interactions among climates, communities, and ecosystems of the future encompasses a wide range of topics in ecosystem and allied sciences (Table 1). Research on basic ecosystem processes (production, consumption, decomposition, nutrient cycling) in these novel ecosystems will produce fundamental information on fluxes of carbon, water, and nutrients over large areas of the earth. However, understanding the dynamics of these systems from a theoretical and mechanistic perspective will be challenging. How will organisms that have not evolved together over long periods of time interact with the environment and each other to produce functional units and respond to environmental change? How will evolution play out in these assemblages to influence function and response to environmental change and disturbance?

## Now That We Have Accepted Humans as Components of Ecosystems, What Do We Do When They Tell Us Things We Do Not Want To Hear?

Over the last 25 years, ecologists have moved from treating people as external drivers, that is, ''outside the box'' agents impacting ecosystems (mostly negatively), to viewing humans as an inherent part of both the challenges of and solutions afforded by urban ecosystems. We have begun to merge traditional ecological approaches and questions with studies in environmental sociology, geography, economics, and psychology, and other social sciences to understand how these perceptions, values, and social institutions influence the behavior of urban residents (Short Gianotti and others 2016). This social-ecological research is a fundamental

**Table 1.** Research Priorities in Urban Ecosystems

1. Predicting or explaining the assembly and function of novel communities and ecosystems under altered environmental conditions:
   a. The emergence of ''novel'' communities and ecosystems, that is, assemblages of organisms and environmental conditions that have not necessarily evolved and assembled in the absence of human action over long periods of time has rekindled interest in using urban areas as sentinels of community and ecosystem response to global change.
   b. Research on basic ecosystem processes (production, consumption, decomposition, nutrient cycling) in these novel ecosystems will produce fundamental information on fluxes of carbon, water and nutrients over large areas of the earth.
   c. How will organisms that have not evolved and assembled over long periods of time interact with the environment and each other to produce functional units and respond to environmental change? How will evolution play out in these assemblages to influence function and response to environmental change and disturbance?
2. Understanding humans as components of ecosystems to create a deeper and more useful understanding of human–environment interactions in the context of integrated social-ecological systems:
   a. How do human values and concerns about the biotic components of urban ecosystems shape the structure and functioning of urban ecosystems?
   b. Co-production of knowledge with stakeholders that takes into account their values and perceptions, even when these values and perceptions are contrary to scientific consensus.
   c. Over the past 20 years, scientists working in urban areas have learned to successfully ''play in a new space.'' Ecosystem ecologists must continue to work with geographers, engineers, sociologists, anthropologists, economists, and others in the ''urban space'' to address fundamental questions about ecosystems and broader issues of sustainability.

advance in environmental science and is facilitating the ability of society to address a wide range of environmental problems from climate change, to the environmental impacts of food production, to the sustainability of our human settlements and the biosphere.

These advances have not come easily. Challenges of working across disciplines (economics, sociology, anthropology, engineering, design, geography, ecology) long a focal topic in this Journal, and the subject of an early special issue (Turner and Carpenter 1999), in collecting data involving people (Cook and others 2004; Grove and others 2015a), and in navigating the interface between basic and applied science have led to uneven progress towards an effective integrated urban systems science and to the emergence of new challenges (McPhearson and others 2016). One of these challenges is to increase our nascent understanding of the ways that the values and concerns that people express about the biotic components of urban ecosystems shape the structure and functioning of urban ecosystems. This challenge likely arises from the difficulties inherent in working across the social science and ecological disciplines to co-generate research questions about the relationships between people and the non-human components of ecosystems. A great advance in environmental science over the past 25 years has been the realization that we need to engage in a dialog with stakeholders to frame ecological questions in contexts that are relevant to these stakeholders rather than just informing (or hectoring) them about what they should value and how they should behave (Groffman and others 2010).

The challenge now is to rework the model of merely passing knowledge and ''educating'' urban residents and policy-makers into one where knowledge is co-produced with stakeholders and thus inherently takes into account their perceptions, values and institutions, even when these are contrary to scientific consensus. For example, the concept of ecosystem services has developed into a policy-supporting, accounting, and evaluation tool (Kremer and others 2015, 2016). This evaluation is meant to occur through increased scientific understanding of the feedbacks between ecosystem functions and their human benefits, as well as the importance of environmental stewardship, management, and planning to ensure these benefits are provided sustainably to urban residents over time (McPhearson and others 2015). And yet, not all ecosystem functions are beneficial, and many ecosystem services remain poorly understood or valued by urban residents and decision-makers due in part to difficulty in communicating environmental values to stakeholders and vice-versa. Traditionally, the biological branch of ecology (as opposed to human ecology) is not a discipline that integrated or addressed normative concerns such as social inequality, political ecology, or diverging value systems. This challenge, which has emerged in a wide range of issues from climate change, to invasive species management, to agriculture and home lawn best-management practices, is a critical constraint on our ability to develop a basic science understanding of human-dominated ecosystems (Harden and others 2014) and to develop solutions to long-standing environmental problems. However, the prospects for progress in addressing this challenge are very promising in urban ecosystems, where the vast majority of human–environment interactions occur and the opportunities for engagement with decision-makers through participatory and transdisciplinary science and citizen science are abundant (Grove and others 2015b).

## Moving Towards a New Urban Systems Science

There is great potential for a new period of urban systems science that will produce fundamental advances in our basic scientific understanding of community assembly and ecosystem structure, function, and response to global environmental change (McPhearson and others 2016). Urban ecosystems offer unique and powerful opportunities to understand the processes involved in the assembly of ecological communities under altered environmental conditions, how novel ecosystems function, how they are likely to persist or change in response to changes in climate and atmospheric chemistry, and how they will interact with social and economic systems over the next several decades. More broadly, the urban system science initiative that we propose here could catalyze the novel interdisciplinary and transdisciplinary research that is fundamental to advancing sustainability science, and to advancing urban sustainability in the cities where we live and work (Childers and others 2014).

What would a new initiative in urban systems science look like? One possible model is the social-ecological-technological-systems (SETS) approach that is guiding a current urban Sustainability Research Network project on Urban Resilience to Extreme Events (http://URExSRN.net) (Grimm and others 2016; McPhearson and others 2016). The SETS approach recognizes that understanding and managing urban ecosystems cannot proceed without consideration of social, ecological, and technological aspects of environmental phenomena and provides a platform for considering and integrating these aspects to address specific research and practical questions. This approach requires a greater integration of the engineering and design disciplines with the natural and social sciences (ACERE-Advisory Committee for Environmental Research and Education 2015).

Over the past 20 years, scientists working in urban areas have learned to successfully ''play in a new space.'' Progress in understanding urban ecosystems cannot be made in isolation. Ecosystem ecologists have learned how to work with geographers, engineers, designers, sociologists, anthropologists, economists, and others in the ''urban space.'' Urban ecosystem ecology is a shining example of how interdisciplinary research develops and produces advances in both basic and applied science. The two directions in urban system science emphasized here: (1) developing the science of community assembly and ecosystem function in human-dominated environments and (2) building on rapid progress in understanding humans as integral components of urban ecosystems will lead to additional progress in some of the most compelling scientific questions in each component discipline and in integrated sustainability science. The environmental challenges of the 21st century require great advances in our understanding of interactions between human and environmental systems to produce knowledge and approaches to enable the development of more ecologically sound, equitable, and economically viable social-ecological systems.

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