Landscape and Urban Planning 125 (2014) 209–221

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Urban ecology and sustainability: The state-of-the-science and future directions

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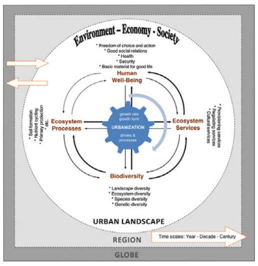
HIGHLIGHTS

- Urban ecology has a history of more than 90 years, with diverse perspectives.
- Urban ecology has become a mainstream ecological field during the past two decades.
- Recent research focuses on urbanization patterns and environmental impacts.
- The most salient thrust of current research is urban sustainability.
- A key topic is urban ecosystem services in relation to human well-being.

GRAPHICAL ABSTRACT

A conceptual diagram illustrating the relationships among biodiversity, ecosystem processes (or ecosystem functions), ecosystem services, and human well-being in an urban landscape. All the components and their relationships are influenced profoundly by the speed and spatiotemporal pattern of urbanization that is driven primarily by socioeconomic processes. Thus, understanding and improving the ecology and sustainability of urban landscapes and regions should not only consider how urbanization affects these key components but also how their relationships change in time. Human well-being is the primary focus for urban sustainability projects, whereas urban ecological studies often focus on biodiversity, ecological processes, and ecosystem services. In either case, the connections among the key components and their linkages across spatial (landscape–region–globe) and temporal (year–decade–century) scales should be taken into account.



ARTICLE INFO

Article history:
Available online 4 March 2014

Keywords:
Urban ecology
Urban sustainability
Urban growth patterns
Biodiversity
Ecosystem services
Human well-being

ABSTRACT

Ecosystems and landscapes around the world have become increasingly domesticated through urbanization. Cities have been the engines of socioeconomic development but also the centers of major environmental problems since the industrial revolution. Numerous studies have shown that our urban ecosystems and landscapes are on an unsustainable trajectory. Global sustainability depends critically on cities, and urban ecology can – and needs to – play a key role in the transition toward sustainability. In this paper, I review different definitions and perspectives of urban ecology, discuss major advances and key issues, and propose a framework to help move the field forward. After almost 90 years of development, urban ecology has evolved into a truly transdisciplinary enterprise that integrates ecological, geographical, planning, and social sciences. The most salient thrust of current research activities in the field is the emerging urban sustainability paradigm which focuses on urban ecosystem services and their relations to human well-being. While urbanization is complex in many ways, we do know a lot about its patterns, processes, and effects. More specifically, we know a great deal about urban growth patterns in space and

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http://dx.doi.org/10.1016/j.landurbplan.2014.01.018

time, the underlying drivers and mechanisms, and myriad effects of urbanization on biodiversity, ecological processes, and ecosystem services. Compared to their ancient counterparts, contemporary cities tend to be bigger in physical size and ecological footprint, faster in growth rate in terms of both population and urbanized land, and more irregular in landscape composition and configuration. As coevolving human-environment systems, cities are spatially heterogeneous, complex adaptive systems. As such, the dynamic trajectory of cities can never be fully predicted or controlled, but can and should be influenced or guided in more desirable directions through planning and design activities that are based on urban ecological knowledge and sustainability principles.

1. Introduction

The world has urbanized at an accelerating rate during the past century, and humans have become a predominantly urban species in that more than 50% of the global population now live in urban areas (Wu, 2008). This global demographic transition has enormous environmental, economic, and social consequences that are yet to be fully understood. At the global scale, the general level of human well-being, as measured by Human Development Index (consisting of three components: life expectancy, GDP per capita, and education), has been steadily rising in spite of (not because of) the widely acknowledged declining trend in ecosystem services during the past several decades (Millennium Ecosystem Assessment, 2005; Raudsepp-Hearne et al., 2010). Multiple possible explanations for this so-called "environmentalist's paradox" have been offered – the prepotency of provisioning services to other ecosystem services, time lags in the relationship between ecosystem services and human well-being, and separation of humans from nature due to technology and social innovation (Raudsepp-Hearne et al., 2010). A better understanding of this seemingly paradoxical global-scale relation, however, requires scrutiny with more detailed data at local and regional scales. In particular, the roles of urbanization in the rise of human well-being and the fall of ecosystem services should be explicitly considered.

Although the urbanized land area dominated by the built environment – "all non-vegetative, human-constructed elements, such as buildings, roads, runways, etc." – occupies a surprisingly small percentage (<1%) of the earth's terrestrial surface (Schneider, Friedl, & Potere, 2010), the effects of urbanization are profound and pervasive from the local to the global scale. Cities now account for about 60% of all residential water use, 75% of energy use, 80% of the wood used for industrial purposes, and 80% of human greenhouse gas emissions (Grimm et al., 2008; Newman, Beatley, & Boyer, 2009). During the past 50 years, global urbanization has not only accelerated its pace in terms of urban population and the built environment, but also taken new developmental forms. These changes have contributed greatly to the domestication of ecosystems, landscapes, and even the biosphere, thus accelerating the arrival of the Anthropocene epoch.

"The future of humanity lies in cities. . . . Weak cities will almost certainly act as a brake on national development. Strong cities can be a key factor enabling a country to thrive in the global economy" (Annan, 2002). If our cities continue to grow and spread the way they have since the industrial revolution, there is little doubt that human civilization is destined to disaster. On the other hand, as engines of socioeconomic development and centers of cultural transformation and techonological innovation, cities can, and will have to, play a critical role in achieving sustainability at the regional and global scale (Wu, 2008, 2010a). Sustainability refers to sustainable development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987), or "meeting fundamental human needs while preserving the life-support systems of planet Earth" (Kates et al., 2001). To help achieve a sustainable urban future, we must understand how urban systems work and how they ought to work. Evidently, urban ecology is essential for developing such an understanding (Loucks, 1994; Wu, 2008, 2010a).

In this paper, I provide an overview of major advances and discuss future directions in urban ecology. Reviewing the history and progress of a burgeoning field like urban ecology is daunting as many aspects of the field are rapidly evolving with ambiguous relationships among them. Nonetheless, several recent attempts have been made, including a number of books in the past few years (Alberti, 2008; Douglas, Goode, Houck, & Wang, 2011; McDonnell, Hahs, & Breuste, 2009; Niemela, 2011; Weiland & Richter, 2011). This paper is neither a summary of these recent works nor a review of everything in urban ecology. Rather, it provides an overview of the state-of-the-science of urban ecology from a landscape perspective, in which urban areas are viewed as spatially heterogeneous human-environment systems – i.e., urban landscapes (Wu, 2008).

2. Evolving definitions and perspectives of urban ecology

2.1. What is urban?

There are diverse definitions of what is "urban." Consequently, a unified definition of urban ecology is nowhere to be found. Different definitions emphasize different aspects of urban systems, and each has advantages and disadvantages, depending on the situation in which it is used. Searching for a universally accepted definition for urban or urban ecology may be neither productive nor necessary. Nevertheless, it is necessary to know how these terms are usually defined (i.e., the meanings of their most common usage) in order to facilitate communication and avoid confusion.

While an urban area (i.e., a town, city, or metropolis) has been defined variously by governmental agencies and individual researchers, most of these definitions are based on one or more of three primary factors: total population size, population density, and impervious surface area or built structures. In general, urban areas share several common characteristics: high population density, abundant built structures, extensive impervious surfaces, altered climatic and hydrological conditions, air pollution, and modified ecosystem function and services (Grimm et al., 2008; McIntyre, 2011; Pickett et al., 2001). However, it is neither feasible nor essential to encapsulate all key components and characteristics of urban areas into one definition. In most cases, high human population density and extensive impervious surface area are two salient factors that sufficiently define what is urban. Essentially all major ecological and environmental characteristics of urban systems can be related to these two factors either directly or indirectly.

2.2. Urban ecology as human ecology and sociology

Urban ecology was originally developed as part of human ecology in the 1920s by a small but influential group of sociologists at University of Chicago (the Chicago school of sociology or human ecology). The key players of the Chicago school included Robert

E. Park (1864–1944), Ernest W. Burgess (1886–1966), Roderick D. McKenzie (1885–1940), and Amos H. Hawley (1910–2009). Park, Burgess, & McKenzie (1925) defined urban ecology as "the study of the relationship between people and their urban environment" – which is essentially human ecology of the city. Human ecology is regarded as "one of the oldest areas of specialization in sociology" (Wilson, 1984b). Urban ecology sometimes was used interchangeably with human ecology (Berry & Kasarda, 1977; Flanagan, 1993; Hollingshead, 1940). In a review of progress in urban ecology, Wilson (1984b) stated, "Urban ecology is not a distinct area of specialization within sociology but rather a body of knowledge about the urban milieu derived by applying a human ecological frame of reference." The emergence and early development of urban ecology took place in a time period when key ecological and sociological ideas influenced each other, often through close interactions between prominent scholars in both fields (Gross, 2002).

In the beginning of urban ecology, social scientists applied ecological concepts such as competition, invasion, dominance, and succession, in their study of social and geospatial organization in cities (Hollingshead, 1940; Park et al., 1925). The surge in applying ecological theory and concepts in social research was not confined within the United States, but also found its way in Europe, Asia, and Africa (Adams, 1935; Hollingshead, 1940). According to Berry and Kasarda (1977), the urban ecology approach was "one of the most definitive and influential schools in American sociology" during the 1930s and 1940s, but "virtually dead" by 1950. Efforts were made to revive the approach by widening its focus and perspectives. One such attempt was Hawley's (1950) classic book, which was intended to provide a unified theory of human ecology. Following the Chicago school tradition and moving beyond it, Berry and Kasarda (1977) presented a "contemporary urban ecology" approach to urban research that cuts across several fields of social sciences: urban sociology, urban geography, social ecology, human ecology, and city and regional planning. This approach embraces a socio-spatial hierarchy with successive levels of neighborhoods, cities, metropolitan areas, regional and urban systems, and total societies. In contrast with traditional human ecology, which relies heavily on "competition as the basis of human organization" and excludes "cultural and motivational factors in explaining land use patterns," the "contemporary" urban ecology emphasizes "interdependence" in the sense of "symbiosis and commensalism (Berry & Kasarda, 1977). Today, the sociological approach to urban ecology continues to exist and evolve (Flanagan, 1993). More broadly, how political systems and institutions affect the spatiotemporal patterns of urbanization has increasingly become a central research issue in social sciences (Gottdiener & Hutchison, 2010; Nassauer & Raskin, 2014; Swaffield, 2013; Wolch, Byrne, & Newell, 2014).

2.3. Urban ecology as an "ecological" science

It is not really surprising that urban ecology was not started by bio-ecologists who focus on plants and animals, and who have long viewed cities as severely impaired ecosystems unworthy of scientific research. Ecosystem ecology and landscape ecology emerged after urban ecology – the terms "ecosystem" and "landscape ecology" were coined in 1935 and 1939, respectively. Until a few decades ago, bio-ecologists had preferred to study "nature without man" (Collins et al., 2000; Wu & Loucks, 1995). Of course, there were exceptions to this general statement even during the early days of urban ecology. Among the most noticeable were a number of European studies of the spatial distribution and abundance of plants and animals in cities during the late 1940s and early 1950s after the World War II (Sukopp, 1990, 2002). These early studies were carried out mainly by botanists and zoologists, representing a bio-ecology approach to urban ecology which has been sometimes dubbed "the Berlin school" (Luck & Wu, 2002; Weiland & Richter, 2011; Wu, 2008).

In North America, Adams (1935), an animal ecologist and a pioneer in ecological energetics, discussed in considerable depth the relationship of general ecology to human ecology. A special issue of Ecological Monographs in 1940, entitled the "relation of ecology to human welfare," evolved out of a symposium organized by the Ecological Society of America upon request from the American Association for the Advancement of Science (Adams, 1940). Stearns (1970) also recognized that biologists in general neglected the urban environment in their studies, and asserted that: "The implications of ecological concepts such as diversity, succession, energy and nutrient flow, population dynamics, and territoriality are pertinent to the management of older cities and the development of new ones."

These studies are important milestones in the history of urban ecology, but they did not change the dominant perception by ecologists that cities were "unworthy" study sites. Urban ecology was hardly visible in the mainstream journals of ecological science before the late 1980s and early 1990s (Grimm, Grove, Pickett, & Redman, 2000; McDonnell, 2011; McDonnell & Pickett, 1990; Pickett et al., 2011, 2001). Several factors may have been responsible for the recent surge of interests in urban areas by bio-ecologists, including the increasing concerns with environmental impacts of urbanization, the rise of ecological views emphasizing non-equilibrium and patch dynamics, and the pervasive influences of the ongoing sustainability movement (McDonnell, 2011; Wu, 2008). The establishment of large-scale interdisciplinary projects, such as the two Long-Term Ecological Research (LTER) projects supported by the US National Science Foundation – the Baltimore Ecosystem Study (BES) and the Central Arizona-Phoenix Long-term Ecological Research (CAP-LTER), has certainly played an important role in the recent rejuvenation of urban ecology (Grimm, Redman, Boone, Childers, & Harlan, 2013; McDonnell, 2011; Pickett et al., 2011). This "new version" of urban ecology is characterized by increased "interdisciplinarity" and "transdisciplinarity" in its dominant research themes as well as its key participants (more discussion on this in the following sections).

2.4. Changing perspectives of urban ecology

The various concepts and perspectives in urban ecology have been categorized as either "ecology in cities," which focuses primarily on the non-human organisms in the urban environment, or "ecology of cities," which considers the whole city as an ecosystem (Grimm et al., 2000; Wu, 2008). Considering the new developments in urban studies during the past decade, here I add a third category – "sustainability of cities." Based on this broad categorization, several distinct but related urban ecological approaches can be identified (Wu, 2008, 2010b). I summarize them below, and their chronology and relationships are illustrated in Fig. 1.

First, the human ecology-based or urban sociological approach investigates human behavior and social organization in cities based on borrowed ecological theory and concepts (e.g., the traditional human ecology approach). Second, the bio-ecology approach focuses on the distribution and abundance of plants and animals in and around cities (e.g., the earlier European studies). Third, the urban systems approach (e.g., Odum, 1983; Stearns & Montag, 1974) or human ecosystem approach (e.g., Pickett et al., 1997; Pickett & Cadenasso, 2006), both of which treat the city as a whole ecosystem consisting of both "natural" and socioeconomic components. Fourth, the urban landscape approach treats urban areas as spatially heterogeneous, multi-scaled patch dynamic systems (Grimm et al., 2000; Pickett et al., 1997; Wu, Buyantuyev, et al., 2011; Zipperer, Wu, Pouyat, & Pickett, 2000). Based on principles and methods in landscape ecology, this approach focuses

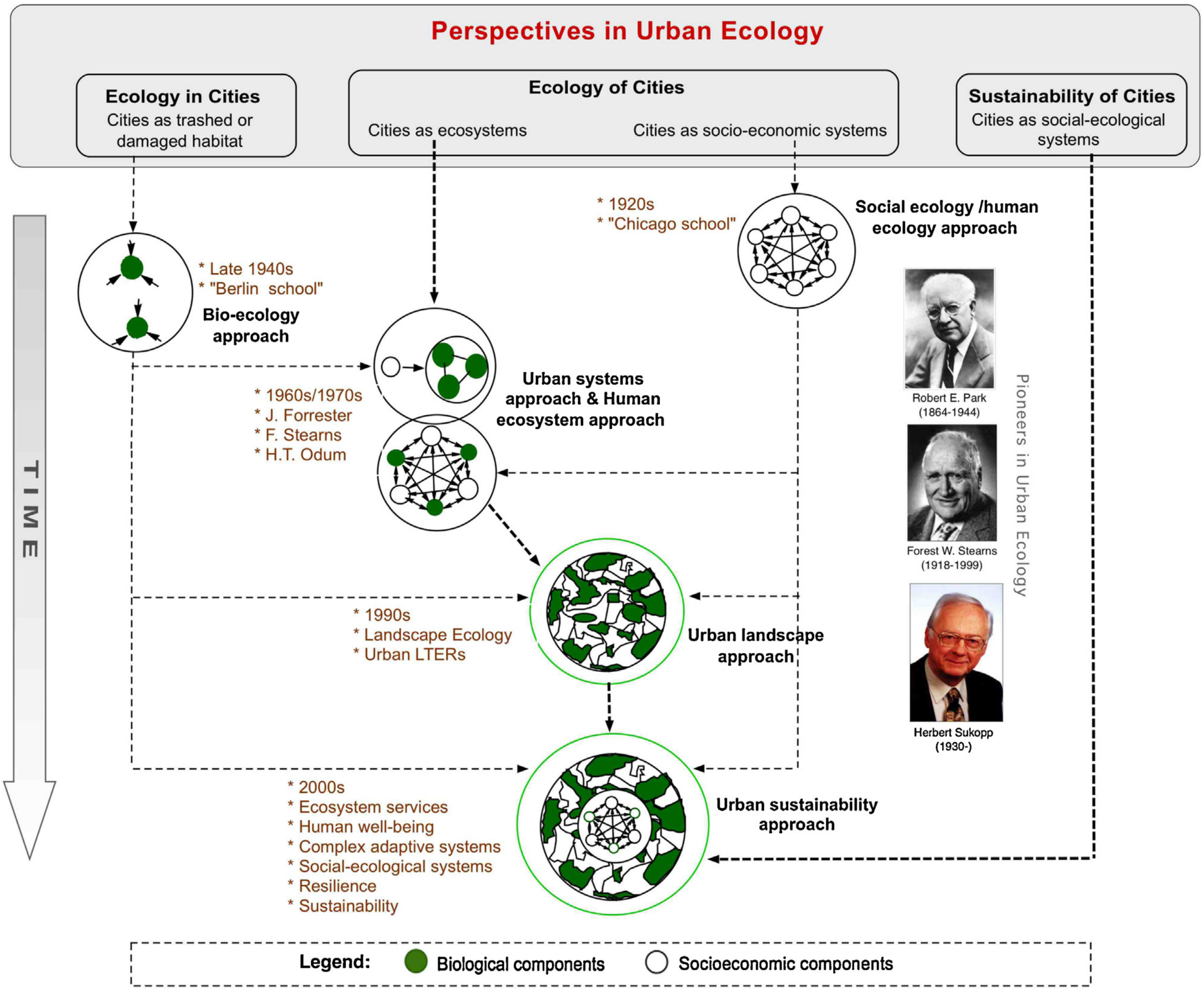

Fig. 1. Evolving perspectives and approaches in urban ecology (modified from Wu, 2008). Different urban ecology approaches, arranged chronologically based on the approximate time of their emergence, are classified into three broad perspectives: ecology in cities, ecology of cities, and sustainability of cities. Dashed lines denote relationships among different approaches and the thickness of the lines denotes the relative strength of influence. During the recent decades, different perspectives tend to merge together, and the field of urban ecology has become increasingly interdisciplinary, dominated by the landscape approach with rising emphasis on urban sustainability.

on the relationship between urbanization patterns and ecological processes (Fig. 2). The fifth is the emerging urban sustainability approach that treats cities as coupled human-environment systems or social-ecological systems, with an increasing emphasis on the relationship between ecosystem services and human well-being in urban areas.

Ecological studies that deal with broad-scale problems in real landscapes eventually have to address the questions of sustainability (Wu, 2013). While some think that "urban sustainability" is an "oxymoron," the term has been increasingly embraced by urban researchers (Ahern, 2013; Alberti, 1996; Grimm et al., 2013; Loucks, 1994; Maclaren, 1996; Musacchio, 2011; Wu, 2010b; Wu & Wu, 2013). However, a generally-accepted definition of urban sustainability is still lacking. As Loucks (1994) articulated:

> "Sustainability is one of those concepts or visions that periodically wash over a society like a storm surge. A mild flooding by more modest concepts may have occurred before, but now almost all the terms we use to describe resources and environment for urban systems must be reassessed in the context of long-term sustainability. This is not simply a concept paradigm shift; rather, the breadth of the dialogue taking place on long-term, intergenerational interests in urban resources is unprecedented."

Maclaren (1996) noted that the terms of "urban sustainability" and "sustainable urban development" are closely related and often used interchangeably in the literature. She further stated that urban sustainability refers to "a desirable state or set of conditions that persists over time" whereas sustainable urban development implies "a process by which sustainability can be attained." Indeed, there seems a belief among the scientific and planning communities that the sustainability concept emphasizes maintaining the status quo or a static steady state of some sort. This is a misconception. As indicated in the Brundtland Report, "sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" (WCED, 1987). Urban sustainability may refer to a set of dynamic conditions that satisfy the needs of current and future generations in an urban area, but it is more fundamentally an ongoing adaptive process of achieving and maintaining those conditions. Partly because of the emphasis on the nonlinear dynamics and

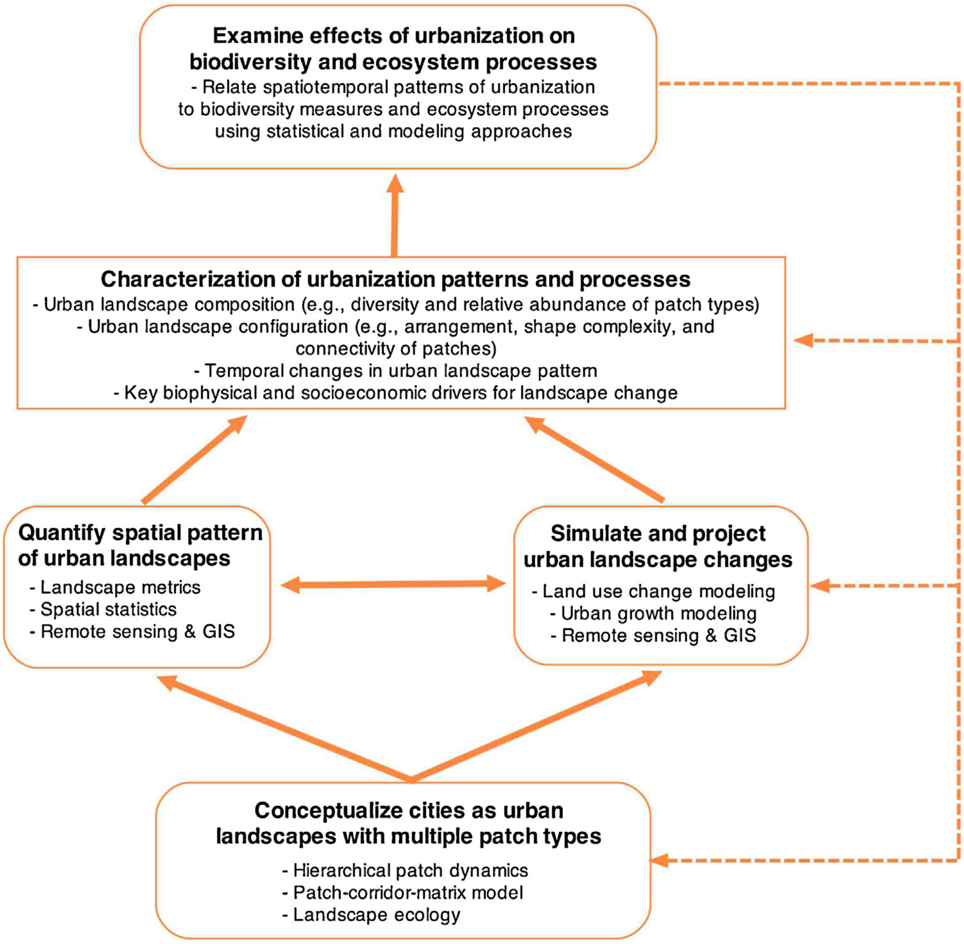

Fig. 2. A hierarchical patch dynamics framework for studying the urbanization pattern and its ecological effects in the Phoenix metropolitan region, USA. (redrawn from Wu et al., 2011a).

adaptive responses in urban systems, urban sustainability and urban resilience have also been increasingly discussed together as complementary rather than contradictory terms (e.g., Wu & Wu, 2013). For the purpose of this review, here urban sustainability is defined as an adaptive process of facilitating and maintaining a virtuous cycle between ecosystem services and human well-being through concerted ecological, economic, and social actions in response to changes within and beyond the urban landscape.

2.5. Toward a comprehensive definition of urban ecology

It is clear from the previous sections that the connotation of the term, urban ecology, has expanded and diversified during the past several decades. Ecologists, as well as urban geographers, planners, and social scientists, all have attempted to define urban ecology in their own preferred ways. For example, Rebele (1994) described urban ecology as "a sub-discipline of ecology" that is "concerned with the distribution and abundance of plants and animals in towns and cities." Quite similarly, Gaston (2010) recently defined urban ecology as "the scientific study of the processes determining the abundance and distribution of organisms, of the interactions between organisms, of the interactions between organisms and the environment, and of the flows of energy and materials through ecosystems ... within urban systems." This is clearly "ecology in cities," reflecting a bio-ecology perspective consistent with the early European studies. From a landscape ecological perspective, Luck and Wu (2002) described urban ecology as the study of understanding "the relationship between the spatial pattern of urbanization and ecological processes." Alberti (2008) defined urban ecology as "the study of the ways that human and ecological systems evolve together in urbanizing regions" – reflecting a widely adopted social-ecological systems perspective in the study of interactions between society and the environment. McDonnell (2011) stated that "urban ecology integrates both basic (i.e. fundamental) and applied (i.e. problem oriented), natural and social science research to explore and elucidate the multiple dimensions of urban ecosystems." In contrast, in the urban planning literature, "urban ecology has focused on designing the environmental amenities of cities for people, and on reducing environmental impacts of urban regions" (Pickett et al., 2011).

All the above definitions are useful, each capturing certain aspects of urban ecology, ranging from bio-ecology components to urban sustainability issues. In general, contemporary urban ecology consists of three kinds of research components that have been integrated increasingly during the past few decades (Fig. 3). Accordingly, urban ecology may be defined as the study of spatiotemporal patterns, environmental impacts, and sustainability of urbanization with emphasis on biodiversity, ecosystem processes, and ecosystem services. Socioeconomic processes and urban planning practices profoundly influence urbanization patterns, and thus contribute to, but cannot alone constitute, the scientific core of urban ecology. This broad definition encompasses the perspectives of "ecology in cities", "ecology of cities", and "sustainability of cities". Urban ecology overlaps with, but differs from, what may be called "urban sustainability science" whose focus is on human well-being that depends fundamentally on ecosystem

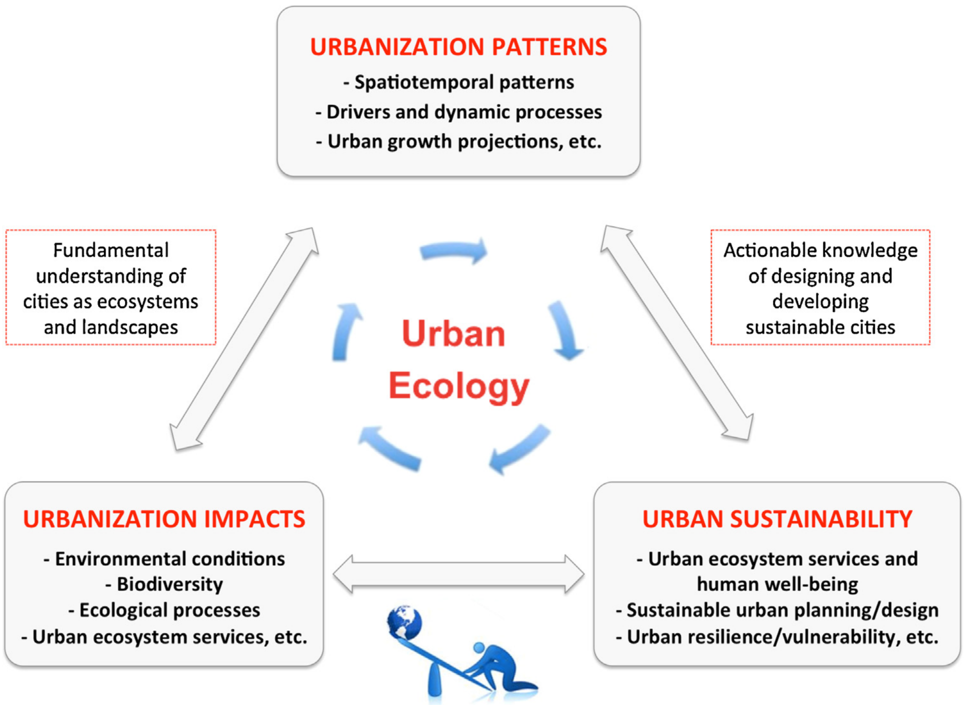

Fig. 3. A triadic conceptualization of contemporary urban ecology, showing that the spatiotemporal patterns, environmental and socioeconomic impacts, and sustainability of urbanization interact with each other in the study of cities, making urban ecology a truly interdisciplinary and transdisciplinary science that integrates research with practice.

services (Millennium Ecosystem Assessment, 2005; Wu, 2013). Urban sustainability science encompasses urban ecology, but is a much broader field of study. Ecosystem services, as benefits that people derive from biodiversity and ecosystem functions, provide a key nexus that links urban ecology and sustainability.

3. Major advances in urban ecology

Several attempts have been made during the past decade to assess the recent developments in urban ecology from different angles (e.g., Alberti, 2008; Grimm et al., 2008; Pickett et al., 2011, 2001; Ramalho & Hobbs, 2012; Wu, Buyantuyev, et al., 2011). In particular, Pickett et al. (2011) provided one of the most comprehensive and updated reviews of urbanization effects on the climate, hydrology, streams, biota, soils, and human society. My intent here is to highlight some of the major advances in the field, following a landscape-oriented framework that I outline below.

This framework is based on the conceptualization that an urban area is a cultural landscape characterized by high population density and extensive impervious surface area, with different land use and land cover types together forming a dynamic patch mosaic (Pickett et al., 1997; Wu, 2006, 2008; Wu & David, 2002; Wu & Loucks, 1995). Thus, an urban system is a spatially heterogeneous landscape whose structure, function, and dynamics are determined by coupled human-environment interactions (Wu, 2010b, 2013). Urban systems also are complex adaptive systems that are characterized by highly diverse components, spatial heterogeneity, nonlinear feedbacks, multi-scale interactions, and ability to self-adjust in response to changes (Levin et al., 2013; Wu & Wu, 2013). Urbanization alters the composition and spatial arrangement of the landscape elements (e.g., remnant natural areas, human-created or managed green-spaces, waterways, agricultural fields, built structures, transportation corridors, and residential areas), and these changes affect the biodiversity, ecosystem functioning, and environmental quality, as well as human behavior, community structure, and social organization. These urbanization-induced ecological and social changes further influence the stocks and flows of different kinds of ecosystem services essential to human well-being in urban areas (Fig. 4). Based on this framework, this section discusses the major advances in several research fronts: the spatial and temporal patterns of urbanization, effects of urbanization on biodiversity and ecosystem processes, and impacts of urbanization on ecosystem services and human well-being.

3.1. *Spatiotemporal patterns of urbanization*

The study of urban spatial patterns includes several aspects, ranging from green-space distribution, waterways, transportation networks, urban growth forms, to urban landscape patterns. My emphasis here is on the quantification of the spatial and temporal patterns of urban landscapes. Landscape pattern – including the composition and spatial arrangement of different kinds of land use and land cover patches – is a comprehensive and realistic representation of the structure of urban ecological systems. Quantifying urban landscape pattern is often necessary for understanding the driving forces (socioeconomic processes and geophysical-environmental characteristics) and ecological impacts of urbanization (Figs. 2 and 3; Wu, Buyantuyev, et al., 2011; Wu, Jenerette, Buyantuyev, & Redman, 2011).

Urban morphology and urban growth form have a long research history. The German economist von Thünen (1825) asserted that an isolated city would assume a form characterized by concentric economic rings (e.g., business, residential, industrial, and agricultural), as dictated by the principle of marginal spatial utility. Influences of this early work are found in some of the classic theories of urban growth pattern, including Burgess's (1925) concentric zone model and Christaller's (1933) central place theory, both depicting cities as a system of concentric zones with one or more central business districts (CBD). In contrast, the sector theory (Hoyt, 1939) and the multiple nuclei theory (Harris and Ullmann, 1945) recognized that transportation networks and interspersed centers of land use functions could lead to asymmetric and patchy urban forms. Like

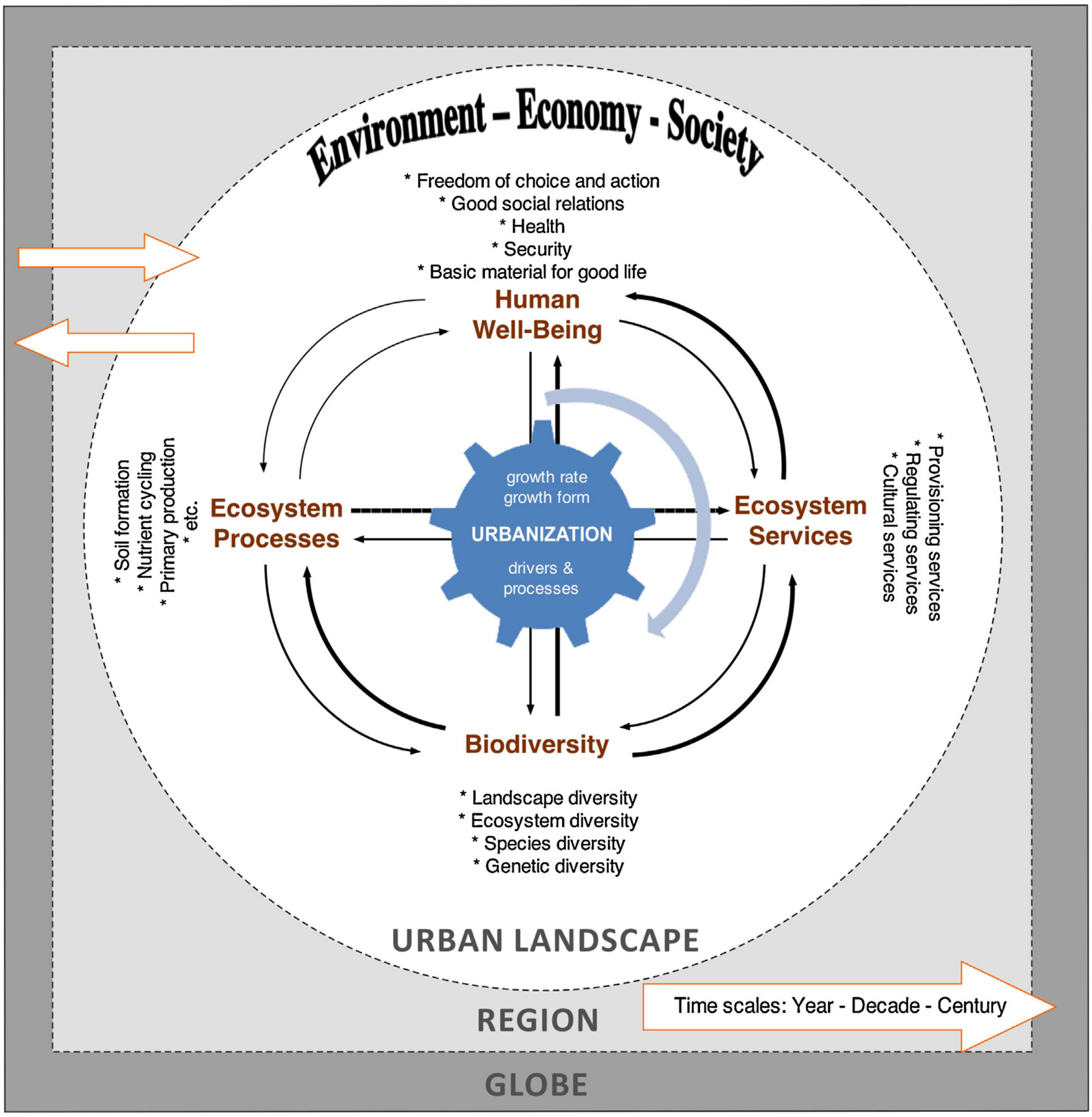

Fig. 4. A conceptual diagram illustrating the relationships among biodiversity, ecosystem processes (or ecosystem functions), ecosystem services, and human well-being in an urban landscape. All the components and their relationships are influenced profoundly by the speed and spatiotemporal pattern of urbanization that is driven primarily by socioeconomic processes. Thus, understanding and improving the ecology and sustainability of urban landscapes and regions should not only consider how urbanization affects these key components but also how their relationships change in time. Human well-being is the primary focus for urban sustainability projects, whereas urban ecological studies often focus on biodiversity, ecological processes, and ecosystem services. In either case, the connections among the key components and their linkages across spatial (landscape–region–globe) and temporal (year–decade–century) scales should be taken into account.

any other general theory in ecology and geography, these classic theories may best be treated as heuristic guides or neutral models because they tend to be the exceptions rather than the norm when applied to real cities (Luck and Wu, 2002).

During the past several decades, much progress has been made in characterizing urban growth patterns in two ways. First, we now have much greater capabilities to analyze the spatial and temporal patterns of urbanization at multiple scales from cities to the entire globe, thanks to continuously improving remote sensing data, GIS techniques, and spatial analysis methods (Buyantuyev, Gries, & Wu, 2010; Herold, Goldstein, & Clarke, 2003; Li, Li, & Wu, 2013; Schneider et al., 2010; Schneider and Woodcock, 2008; Wu, Buyantuyev, et al., 2011; Wu, Jenerette, et al., 2011). Second, a more comprehensive understanding of urban growth form has been achieved through the combination of theoretical development and empirical case studies (Batty, 2005; Batty and Longley, 1989; Wu, Buyantuyev, et al., 2011; Wu, Jenerette, et al., 2011).

Numerous studies in geography and landscape ecology have shown that, compared to historical patterns, contemporary urbanization is bigger in city size, faster in growth rate, and more irregular in urban form; and that urban agglomeration and landscape structural homogenization have become a global trend (Herold et al., 2003; Jenerette and Potere, 2010; Jenerette and Wu, 2001; Li et al., 2013; Schneider et al., 2010; Schneider and Woodcock, 2008; Seto, Sanchez-Rodriguez, & Fragkias, 2010; Wu, Buyantuyev, et al., 2011; Wu, Jenerette, et al., 2011). Also, the rate of urbanization during the past several decades has been much faster in developing countries than in developed countries, and there seems to be a convergence in the urban physical structure toward the appearance of North American cities (Seto et al., 2010). The global trend of decreasing landscape structural heterogeneity has been related to the homogenization of biological diversity worldwide (Jenerette and Potere, 2010; McKinney, 2006).

Also, the fractal features of urban forms have been widely recognized, and city size-based scaling patterns have long been investigated (Batty, 2006, 2008; Batty and Longley, 1989; Bettencourt and West, 2010; Bettencourt, Lobo, Helbing, Kühnert, & West, 2007; Glaeser, 2011). Of course, the spatial and temporal patterns of local and regional urban landscapes vary geographically because of differences in physical environments, socioeconomic drivers, and land use policies. Principles and methods in landscape ecology and land change science can help handle these complex issues. Techniques in remote sensing, GIS, and spatial analysis and modeling have continued to improve rapidly, so has our overall capability to understand the spatiotemporal patterns of urbanization. A number of recent reviews on this topic are available (e.g., Batty, 2005; Batty, Barros, & Junior, 2006; Berling-Wolff and Wu, 2004; Jenerette and Wu, 2001; Matthews, Gilbert, Roach, Polhill, & Gotts, 2007; Milne, Aspinall, Veldkamp, 2009; Verburg and Overmars, 2009; Wu, Buyantuyev, et al., 2011; Wu, Jenerette, et al., 2011).

3.2. Urban biodiversity

Assessing how urbanization affects biodiversity and ecological conditions has been a major research focus in most ecological and environmental studies of cities during the past several decades (Figs. 1 and 3). Such "impact studies" are numerous, ranging from small towns to major metropolitan regions and beyond. Major species groups studied include plants, birds, terrestrial arthropods, but relatively few studies have focused on non-avian vertebrates and non-arthropod invertebrates, such as reptiles, amphibians, mammals, fish, and aquatic invertebrates (McIntyre, 2011; McKinney, 2006, 2008; Pickett et al., 2011, 2001; Rebele, 1994).

Urban development decreases the amount of habitat for native species and increases habitat fragmentation for most native and exotic species. In general, the effects of urbanization on biodiversity vary with taxonomic groups, environmental conditions, and socioeconomic settings. However, several general findings have emerged. For example, with increasing urbanization, plant species richness tends to increase due mainly to the increase in exotic species; bird species richness tends to be relatively constant or increase moderately, with a decrease in evenness; and the diversity and abundance of soil fungi and microbes tend to decrease (Marzluff, 2005; McIntyre, 2011; McKinney, 2008; Pouyat et al., 2008; Rebele, 1994; Wu, Buyantuyev, et al., 2011). Urbanization also alters the food web structure and trophic dynamics in the natural remnant ecosystems in the urban landscape. Researchers at CAP-LTER reported that a decrease in predation pressure on birds increased the abundance of certain avian species, and that the top-down control of arthropod herbivores by avian predators was much stronger in urban than rural areas (Faeth et al., 2005; Shochat, Warren, Faeth, McIntyre, & Hope, 2006). Studies have also shown that, within an urban landscape, richer neighborhoods tend to be "greener" and have higher levels of plant diversity (Buyantuyev and Wu, 2009; Hope et al., 2003; Iverson and Cook, 2000; Jenerette et al., 2007; Jenerette, Harlan, Stefanov, & Martin, 2011) – a phenomenon known as the "luxury effect" (Hope et al., 2003).

On the global scale, not only do cities share some common species that all are adapted to urban environments, but also urbanization is considered a major cause for the ongoing "biotic homogenization" – different geographic areas tend to have a similar set of species (Lockwood and McKinney, 2001; McKinney, 2006). As mentioned earlier, urbanization tends to homogenize urban landscape pattern, thus reducing habitat heterogeneity for biological species, and this landscape homogenization may be an important reason for the observed biotic homogenization (Jenerette and Potere, 2010; McKinney, 2006).

3.3. Ecosystem processes and conditions

It is well documented that human activities in urban environments have resulted in a series of notorious environmental problems, such as greenhouse gas emissions, air and water pollution, and solid wastes. There is also an extensive literature on the effects of urbanization on climatic conditions, soil properties, hydrology, biogeochemical cycling, and vegetation phenology (Douglas et al., 2011; Niemela, 2011; Wu, 2008; Wu, Buyantuyev, et al., 2011).

Cities are the major producers of greenhouse gases and air pollutants that cause health problems for humans and the environment. Urbanization can significantly influence local and regional climate through altering the land cover pattern and consequently the surface radiation regime and energy balance. The best-studied example of anthropogenic climate modifications is probably the urban heat island (UHI) effect – cities tend to have higher air and surface temperatures than their rural surroundings (Oke, 1982, 1995; Voogt, 2002). Large temperature increases usually occur during nighttime, and the strengths and effects of UHIs vary among cities with different biophysical and socioeconomic conditions (Buyantuyev and Wu, 2010, 2012; Oke, 1995; Pickett et al., 2011; Wu, Buyantuyev, et al., 2011). The UHI over a city or a metropolitan region is composed of many smaller UHIs, forming a spatially nested hierarchy of UHIs that are related to the spatial arrangement of land covers (Buyantuyev and Wu, 2010; Li et al., 2011; Myint, Brazel, Okin, & Buyantuyev, 2010). A number of studies have reported the effects of UHI on the local climate, plant growth and phenology, energy consumption for cooling and heating, and social well-being (Grimm et al., 2008; Jenerette et al., 2007, 2011; Oke, 1995).

Urbanization influences the hydrological cycling and stream flows in the urban landscape through increased water use, water contamination, impervious surfaces, altered runoff patterns, and modified evapotranspiration rates (Pickett et al., 2011, 2001). Urban soils are often physically disturbed, chemically contaminated, or variably affected by management practices (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006; Pickett et al., 2011). Urban soils tend to have a high degree of spatial heterogeneity, large pools of soil organic matter, carbon, nitrogen, and other elements, and many human-made compounds ranging from biological control agents, novel pollutants, hormones, to nanoparticles (Jenerette, Wu, Grimm, & Hope, 2006; Pouyat et al., 2008; Wu, Buyantuyev, et al., 2011; Zhang, Wu, Grimm, McHale, & Buyantuyev, 2013). The changes in climate, hydrology, biota, and soils together result in a "distinct urban biogeochemistry" in which the stocks and fluxes of energy and elements are controlled largely by human activities (Grimm et al., 2008, 2013; Kaye et al., 2006; Pickett et al., 2011). Urban landscaping and management activities may substantially influence the timing, duration, and magnitude of biogeochemical processes (Grimm et al., 2013).

As a consequence of land use and land cover change as well as altered biophysical conditions resulting from urbanization, the vegetation cover of urban landscape changes dramatically in space and time. Net primary production (NPP), the rate at which plant biomass accumulates in an ecosystem, is a key integrative variable of ecosystem function. NPP varies considerably among different land cover types within the city and along the urban-rural gradient, and may either decrease or increase with urbanization at the urban landscape scale (Buyantuyev & Wu, 2009, 2012; McDonnell & Pickett, 1990; McDonnell et al., 2009; Shen, Wu, Grimm, & Hope, 2008; Wu, Buyantuyev, et al., 2011; Zhang, Wu, Grimm, McHale, & Buyantuyev, 2013). For example, in dryland environment, irrigation makes urban green spaces much more productive than the surrounding natural desert, and thus the aboveground NPP of the urban landscape is enhanced (Buyantuyev and Wu, 2009). The close relationship between vegetation growth and precipitation commonly found in natural ecosystems is effectively decoupled for agricultural and urban green spaces in such arid environments (Buyantuyev & Wu, 2009, 2012).

Vegetation phenology or landscape phenology – the timing and duration of plant development phases triggered by environmental factors (e.g. temperature and moisture) – is also affected by urbanization (Neil and Wu, 2006). Urban land transformations may lead to phonological changes of vegetation through altering hydrological flow paths and soil moisture conditions in cities (Buyantuyev and Wu, 2012; Neil and Wu, 2006; Wu, Buyantuyev, et al., 2011). By altering temperature and moisture conditions, UHIs may induce changes in plant phenology and vegetation dynamics in terms of both the timing and duration of growth and flowering (Buyantuyev and Wu, 2012; Neil, Landrum, & Wu, 2010; Neil and Wu, 2006). For example, both leafing and flowering phenology in the Phoenix area have responded to urbanization: urban vegetation covers tend to green-up faster than the natural desert and stay photosynthetically active for a longer period (Buyantuyev and Wu, 2012); and plant species have either advanced or delayed their flowering (Neil et al., 2010).

3.4. Urban ecosystem services and human well-being

Biodiversity provides the basis for ecosystem processes and, in general, increases ecosystem functions such as primary production, soil nutrient retention, and resilience against disturbances and invasions. Ecosystem functions are essentially the different roles ecological processes play in an ecosystem, and the two terms – ecosystem functions and ecosystem processes – often are used interchangeably. Biodiversity and ecosystem functions (or processes) together underpin the natural capital stock which produces goods and services for human societies (Figs. 3 and 4) (Costanza and Daly, 1992; Costanza et al., 1997; De Groot et al., 2002). Since the 1990s, ecosystem services has become an essential concept in conservation, resource management, environmental economics, and sustainable development. This surge of interest has been further solidified by the Millennium Ecosystem Assessment between 2001 and 2005 that provided the first global-scale scientific appraisal of the conditions and trends of the world's ecosystems and their services.

The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) defined ecosystem services as "the benefits people obtain from ecosystems" which include: (1) "provisioning services" (e.g., food and water), (2) "regulating services" (e.g., purification of air and water, regulation of climate, floods, diseases, hazard, and noise), (3) "cultural services" (e.g., recreational, spiritual, religious and other nonmaterial benefits), and (4) "supporting services" (e.g., soil formation, primary production, and nutrient cycling). As supporting services are really ecosystem processes or functions, ecosystem services hereafter refer only to provisioning, regulating, and cultural services, as in Grimm et al. (2013).

Although cities were viewed as severely damaged or "unworthy" ecosystems by bio-ecologists until recently, urban landscapes provide a number of important ecosystem services for urban populations, some of which have long been recognized by planners and social scientists. There has been a rapid increase in urban ecosystem services research in recent years, and most studies so far have focused on green spaces and water bodies. Depending on their design and management, urban green spaces can purify air and water, moderate local climate, sequester CO_2, reduce soil erosion, alleviate noise pollution, provide habitats for plants and animals, increase real estate values, improve neighborhood and landscape esthetics, and enhance human psychological well-being (Bolund and Hunhammar, 1999; Lundy and Wade, 2011; Pataki et al., 2011; Termorshuizen and Opdam, 2009; Tratalos, Fuller, Warren, Davies, & Gaston, 2007; Wu, 2008; Young, 2010). A large number of studies have documented that urban green (vegetation) and blue (water) spaces provide various ecological, environmental, economic, and socio-cultural benefits. For example, in their study of Stockholm, Bolund and Hunhammar (1999) identified seven types of local ecosystems: street trees, lawns and parks, urban forests, cultivated land, wetlands, lakes and sea, and streams. These local ecosystems provided six "local and direct services:" (1) air filtration, (2) climate regulation, (3) noise reduction, (4) rainwater drainage, (5) sewage treatment, and (6) recreational and cultural values; and these ecosystem services had a "substantial impact on the quality-of-life" in the urban area (Bolund and Hunhammar, 1999).

It is important to note that the cultural services of urban landscapes are essential for the well-being of humans as an increasingly urban species. The Millennium Ecosystem Assessment (2005) defined cultural ecosystem services as "nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and esthetic experiences." Cultural services are diverse, including recreation and tourism, cultural identity, heritage values, spiritual services, inspiration, and esthetic appreciation (Daniel et al., 2012; Millennium Ecosystem Assessment, 2005). The recently completed UK National Ecosystem Assessment (2011) further pointed out that cultural ecosystem services are "inscribed with not only natural features but also the legacies of past and current societies, technologies, and cultures." This elaboration is particularly important for urban landscapes.

Wilson (1984a) and Kellert and Wilson (1993) argued that people, when isolated from nature, will suffer psychologically, which may lead to a measurable decline in well-being – the Biophilia Hypothesis. Empirical studies from environmental and social psychology, among others, seem to support this general notion (Kennedy, Dombeck, & Koch, 1998; Kuo and Sullivan, 2001; Miller, 1997; Platt, Rowntree, & Muick, 1994; Ulrich, 1984; Wolch et al., 2014). For instance, in a classic study of this sort, Ulrich (1984) found that patients viewing trees from their room windows everyday had happier moods and faster recovery rates than patients whose windows faced a brown brick wall. Although studies have shown that urban vegetation, in certain situations, may be positively correlated with higher levels of fear and crime rates, Kuo and Sullivan (2001) reported that urban residents living in greener neighborhoods had "lower levels of fear, fewer incivilities, and less aggressive and violent behavior." Recent studies also have shown that stresses associated with the city environment may increase the rate of mental health disorders, such as depression, anxiety, and schizophrenia (Abbott, 2012; Kennedy and Adolphs, 2011; Lederbogen et al., 2011). More broadly, Nassauer and Raskin (2014) found that "landscapes that look well-cared-for discourage abandonment and crime," suggesting that urban landscape attributes other than green space also need to be considered in assessing urban ecosystem services.

Evidence is mounting that urban green (vegetation) and blue (water) spaces – the primary sources of ecosystem services in cities – promote both the ecosystem integrity and human well-being of urban areas. However, increasing green space itself does not guarantee the provision of expected ecosystem services. For example, Nassauer and Raskin (2014) have shown that vacant land parcels, when uncared for, may present safety and health hazards, and thus enhancing "physical evidence of care" through urban planning and design is important for promoting ecosystem services and human well-being in urban areas (Nassauer and Raskin, 2014). Also, urban greening can also lead to unintended environmental injustice issues such as "ecological gentrification," a problem referred to as the "paradox of urban green space" by Wolch et al. (2014). Most of these studies were based on correlation analysis, and the underlying causes and mechanisms of how urban landscape pattern affects human and social well-being are yet to be explored in depth.

In general, cultural ecosystem services have been least studied among the different types of ecosystem services partly because most cultural services are intangible and nonmaterial (Daniel et al., 2012; Schaich, Bieling, & Plieninger, 2010). Also, the relationship between ecosystem services and human well-being in urban environment is yet to be fully explored. To improve this situation, it is necessary to integrate research methods and findings from several fields, including cultural (human) geography, environmental psychology, sociology, landscape ecology, and urban planning and design (Schaich et al., 2010; Termorshuizen and Opdam, 2009). Without adequate consideration of cultural services, a partial ecosystem services approach may lead to extremely partial utilitarian conclusions. Such imbalanced ecosystem services approach can be a "disservice" to our endeavor toward urban sustainability.

4. Toward an urban sustainability paradigm

Ongoing urban ecological studies suggest an emerging sustainability-centered paradigm. This urban sustainability paradigm integrates the previous perspectives and identifies sustainability as the ultimate goal of studying cities – a goal that cannot be achieved by any traditional discipline or approach alone. This new paradigm has only started to take form, and its theoretical foundation and working principles are still being developed. Nevertheless, several outstanding features of the emerging urban sustainability paradigm have become increasingly clear in the past few years.

First, recent urban ecological studies have increasingly taken a landscape perspective (Ahern, 2013; Forman, 2008b; Jones et al., 2013; Lee, Yeh, & Huang, 2013; Musacchio, 2009, 2011; Potschin and Haines-Young, 2013; Wu, 2008, 2010b). Of course, urban planners and geographers always deal with the city as a landscape that has patches, corridors, and the matrix (Forman 1995, 2008a, 2008b). But for most other ecologists, studying the city in a spatially explicit manner or choosing the urban landscape – including the city and its surrounding area (e.g., the urban-rural gradient and hierarchical patch dynamics approaches) – as the study site is relatively new. The urban landscape perspective has a number of benefits (Forman, 2008a, 2008b; Wu, 2008). One of them is to provide a common platform – the landscape – for ecologists, geographers, social scientists, planners, and engineers to work together in order to "mold the land so nature and people both thrive longterm" (Forman, 2008a).

Second, the field of urban ecology has become increasingly transdisciplinary in terms of goals (sustainability-oriented), methods (from both natural and social sciences), participants (scientists, practitioners, decision makers, and stakeholders of many kinds). This seems a necessary consequence of the field moving toward urban sustainability as its ultimate goal in theory and practice. The landscape perspective has certainly facilitated this ongoing transdisciplinary evolution in urban ecology.

Third, ecosystem services and their relationship to human well-being have become a major focus of the current urban ecological studies (Jenerette et al., 2011; Jones et al., 2013; Nassauer and Opdam, 2008; Pickett et al., 2011; Potschin and Haines-Young, 2013; Standish, Hobbs, & Miller, 2013; Swaffield, 2013). This is not surprising because ecosystem services and their relationship to society are essential components of sustainability. Without their importance to human well-being, ecosystem services would not be services; without their relevance to ecosystem services, biodiversity and ecosystem processes in cities probably would never receive so much attention from mainstream ecologists and the like.

Fourth, there has been a proliferation of frameworks proposed for studying and achieving urban sustainability during the past decade: for example, the human ecosystem framework (Pickett et al., 1997; Pickett and Cadenasso, 2006), the hierarchical patch dynamics framework (Wu and David, 2002; Wu & Loucks, 1995; Zipperer et al., 2000), the urban resilience framework (Ahern, 2011, 2013; Cumming, 2011; Cumming, Olsson, Chapin, & Holling, 2013; Resilience Alliance, 2007; Wu and Wu, 2013), the sustainable landscape architecture framework (Chen and Wu, 2009; Nassauer and Opdam, 2008; Turner, 2010), the landscape sustainability framework (Musacchio, 2009; Potschin and Haines-Young, 2006; Wu, 2006, 2008, 2012, 2013), and the urban social-ecological system framework (Grimm et al., 2013). As urban sustainability is a new and extremely complex transdisciplinary topic, it is formidable to approach it without a framework to follow. What is encouraging, though, is that most of the frameworks seem to converge to a few fundamental concepts and theories: ecosystem services, resilience and sustainability, complex adaptive systems (CAS), and social-ecological systems (SES) or coupled human-environment systems. This seems to indicate that the existing frameworks may coalesce and even evolve into fewer but more comprehensive, cohesive, and operational frameworks – a development much needed for moving the field forward.

Fifth, as planning and design have become an increasingly important component of the urban sustainability paradigm, adaptive planning and design as a longitudinal experimental approach is gaining momentum (Ahern, 2013; Cumming et al., 2013; Golley and Bellot, 1991; Nassauer and Opdam, 2008; Swaffield, 2013; Xiang, 2013). This is an exciting and promising direction, as, quite simply, we will not achieve urban sustainability without environmentally, socially, and economically sound design and planning. Urbanization so far has been "a massive, unplanned experiment in landscape change" (Niemela et al., 2011). Such situation must be rectified, and crucial lessons about how to build sustainable cities can be learnt from "safe-to-fail" design and planning experiments (Ahern, 2011, 2013).

5. Concluding remarks

Urban ecology started as part of human ecology or sociology in the 1920s, and bio-ecologists began to develop their version of urban ecology after the late 1940s (Fig. 1). Historically, several parallel approaches to urban ecology have evolved with little interaction between them until quite recently. It is during the past decade or so that the different perspectives in urban ecology have begun to coalesce and integrate. Urban ecology has come of age, and is now considered mainstream in ecology (McDonnell, 2011; Pickett et al., 2011). Today, we are witnessing the burgeoning of a golden age of urban ecology. Unlike many other fields of study that wax and wane in their popularity, the study of urban ecology and sustainability will most likely stay "hot" because our present and future depend on it.

Although urban sustainability has now risen to prominence in urban studies, a generally acceptable and operational definition is yet to be developed. As cities are spatially heterogeneous, complex adaptive systems, however, urban sustainability is more usefully viewed as a dynamic process instead of a fixed goal. No city is sustainable without ecosystem services from outside (Collins et al., 2000; Luck et al., 2001), but an urban landscape or region may be more likely to be sustainable if properly designed, planned, and managed (Forman, 2008a, 2008b; Wu, 2008, 2013). To achieve this goal, "localization" or "regional self-reliance" seem necessary, in most if not all situations, to shorten the production-supply-consumption chain, increase resource use efficiency, minimize externalities, maximize internal regenerative capacity, balancing tradeoffs among different ecosystem services, and enhance the sense of place (see, for example, De Young and Princen, 2012; Chappell, 2013). Some components of cities or even some cities as a whole may be viewed as "novel ecosystems" in which the value of biodiversity should not be judged by its origins (Davis et al., 2011; Standish et al., 2013). Instead, we should "organize priorities around whether species are producing benefits or harm to biodiversity, human health, ecological services and economies" (Davis et al., 2011), and those alien (but not invasive) species that provide abundant ecosystem services should be incorporated into urban planning and management (Clark and Nicholas, 2013; Davis et al., 2011; Standish et al., 2013).

To conclude, let me cite what Robert E. Park said more than 80 years ago:

> "For the city and the urban environment represent man's most consistent and, on the whole, his most successful attempt to remake the world he lives in more after his heart's desire. But if the city is the world which man created, it is the world in which he is henceforth condemned to live. Thus, indirectly, and without any clear sense of the nature of his task, in making the city man has remade himself" (Park, 1929).

The coevolution continues. Future cities will reflect who we are, what we value, and how well we can "remake" our world. Park (1929) viewed the city as "a social laboratory" and as "the natural habitat of civilized man." Today, we may consider the city as a key laboratory for human-environment interactions and urbanization as a global experiment on sustainability. We do not know how the experiment will turn out; but we know the significance of the outcome: it will determine the fate of the human species. Therefore, urban ecology has to embrace sustainability in its scientific core and as its ultimate goal. Indeed this is happening, but the journey has just begun.

Acknowledgements

I would like to thank Joan Nassauer, Wei-Ning Xiang, and two anonymous reviewers for helpful comments on an earlier version of the paper. My research in urban ecology and sustainability science has been supported in part by National Science Foundation under Grant Nos. DEB 9714833, DEB-0423704, and BCS-1026865, Central Arizona-Phoenix Long-Term Ecological Research (CAP-LTER) and BCS-0508002 (Biocomplexity/CNH), as well as a grant from U.S. Environmental Protection Agency's Science to Achieve Results (STAR) program (R827676-01-0).

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