Urban Ecosyst (2012) 15:795–807
DOI 10.1007/s11252-012-0240-9

A comparative gradient approach as a tool for understanding and managing urban ecosystems

Christopher G. Boone · Elizabeth Cook · Sharon J. Hall · Marcia L. Nation · Nancy B. Grimm · Carol B. Raish · Deborah M. Finch · Abigail M. York

Published online: 9 May 2012

Abstract To meet the grand challenges of the urban century—such as climate change, biodiversity loss, and persistent poverty—urban and ecological theory must contribute to integrated frameworks that treat social and ecological dynamics as interdependent. A socio-ecological framework that encapsulates theory from the social and ecological sciences will improve understanding of metropolitan dynamics and generate science for improved, sustainable management of urban ecosystems. To date, most urban ecological research has focused on single cities. A comparative approach that uses gradients within and between cities is a useful tool for building urban ecological theory. We offer five hypotheses that are testable using a comparative, gradient approach: (i) the current size, configuration, and function of larger metropolitan ecosystems predicts the potential trajectory of smaller urban areas; (ii) timing of growth explains the greatest variance in urban ecosystem structure and function; (iii) form and function of urban ecosystems are converging over time; (iv) urban ecosystems become more segregated and fragmented as populations increase; and (v) larger cities are more innovative than smaller cities in managing urban ecosystems.

C. G. Boone (✉)
School of Sustainability, Arizona State University, P.O. Box 875402, Tempe, AZ 85287-5502, USA
e-mail: cgboone@asu.edu

E. Cook · S. J. Hall · N. B. Grimm
School of Life Sciences, Arizona State University, Tempe, AZ, USA

M. L. Nation
Global Institute of Sustainability, Arizona State University, Tempe, AZ, USA

C. B. Raish
USDA Forest Service, Rocky Mountain Research Station, Albuquerque, NM, USA

D. M. Finch
USDA Forest Service, Rocky Mountain Research Station, Albuquerque, NM, USA

A. M. York
School of Human Evolution & Social Change, Arizona State University, Tempe, AZ, USA

Keywords Comparative urbanism · Gradients · Spatial heterogeneity · Convergence · City size · Neighborhood age

Introduction

We are living in the urban century, one that will witness profound consequences for humanity and the environment, yet dominant urban theories and planning practices continue to treat social and economic realms as separate from biophysical systems. Clearly, however, cities are ecosystems (Grimm et al. 2000). As densely settled sites with intensive energy, material, and information fluxes, urban areas transform and are transformed by social *and* ecological processes at multiple scales through time (Pickett et al. 2008). Treating cities as ecosystems, using an integrated socio-ecological framework, is an important starting point for understanding how cities function and for developing more sustainable ways to manage metropolitan areas (Alberti 2008; Alberti and Marzluff 2004; Douglas 2011; Newman and Jennings 2008; Niemelä et al. 2011b, c). In this review, we discuss limits and possibilities of the dominant theories of urbanization and suggest ways to improve understanding and management of urban ecosystems using a socio-ecological framework and a comparative gradient approach. This paper illustrates the utility of such an approach and offers five innovative hypotheses that flow from an ecologically informed theoretical framework on urbanization.

Urban theory

Fundamental to most urban theory is the concept that cities grow because of the wealth generated from agglomeration economies, or the economic benefits that come from living and working in close proximity to others (Knox 2008; Short 2006). Agglomeration leads to greater and more specialized divisions of labor, and expanded opportunities for exchange of goods, services, and information. These processes generate wealth that can be reinvested in buildings, equipment, infrastructure, or more employees, leading to even greater economies of agglomeration, further wealth generation, and consequent urbanization (Batty 2008). Economic cycles have also been used to explain the boom and bust processes of urbanization. Rhythms of urbanization have been shown to match short Kuznets (25 years) and long-wave Kondratieff (50–55 years) cycles of economic growth and decline (Berry 1991). Configuration and functioning of the city are therefore defined largely by the investment in technology and infrastructure that occurs during the growth side of such waves. These waves of investment have long-term impacts, because such things as roads and buildings are fixed investments and can shape the structure and function of cities for many decades. Economic theory has also been employed to explain how initial investment in one technology may create a path dependency, where viable or better alternatives become too costly to implement (Melosi 2005). More recently, theorists have examined the role of neo-liberal political economies in explaining the fates of metropolitan areas, such as the de-industrialization and hollowing out of central cities in the face of intense global competition (Knox 2008). Some larger metropolitan areas, especially in rich countries, enjoy growth and wealth benefits that accrue from the global exchange of capital and information. These ‘global cities’–such as London, New York, or Tokyo–often politically and financially dominate national systems of cities as well (Sassen 2001).

Reliance on economic drivers in urban theory happens for good reasons. Certainly the growth of cities in population and physical extent parallels significant shifts in economy and technological development; no nation became urban before the industrial revolution and the

Table 1 Potential urban gradients within Australia, Germany, and the United States

	Urban area	Population[4]	Area (km^2)	Population density per km^2	Mean annual precipitation (mm)	Mean minimum temperature (°C)	Mean maximum temperature (°C)
USA[1]	Phoenix	4,192,887	2069	2027	203	17.4	30.4
	Albuquerque	887,077	580	1529	240	7.1	21.3
	Las Cruces	209,233	166	1260	234	7.8	25.2
Australia[2]	Melbourne	4,077,036	7693	530	650	10.2	19.8
	Adelaide	1,203,186	1827	659	446	11.4	21.5
	Bendigo	91,713	494	186	515	7.8	20.9
Germany[3]	Berlin	3,460,725	892	3880	571	6.0	13.0
	Leipzig	522,883	297	1761	508	4.3	14.3
	Jena	105,129	114	918	600	7.4	13.8

[1] US Census Bureau http://factfinder2.census.gov Accessed 31 December 2011; US Census Bureau, Population and Area of US Metropolitan Areas. http://www.census.gov/geo/www/ua/ua2k.txt . Accessed 27 August 2010; National Weather Service Forecast Office Phoenix, AZ http://www.wrh.noaa.gov/psr/ Accessed 31 December 2011; National Weather Service Forecast Office Albuquerque, NM http://www.srh.noaa.gov/abq/ Accessed 31 December 2011; State University, New Mexico (298535) Period of Record Monthly Climate Summary http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmstat Accessed 31 December 2011

[2] Australian Bureau of Statistics, National Regional Profile: Melbourne (Statistical Division),

National Regional Profile: Adelaide (Statistical Division), National Regional Profile: Greater Bendigo City Part A (Statistical Subdivision) www.abs.gov.au Accessed 31 December 2011;

Australian Government Bureau of Meteorology Summary statistics Melbourne Regional Office, Summary statistics Adelaide Airport, Summary statistics Bendigo Airport http://www.bom.gov.au/climate/ Accessed 31 December 2011

[3] Stadt Leipzig http://www.leipzig.de/int/en/stadt_leipzig/zahlen/bevoelkerung/stand/ Accessed 31 December 2011; City Population Berlin, Germany http://www.citypopulation.de/php/germany-berlin.php Accessed 31 December 2011; One World Nations Online, Berlin http://www.nationsonline.org/oneworld/Germany/berlin.htm Accessed 31 December 2011; World Weather Online, Jena Weather, Germany Weather Averages

http://www.worldweatheronline.com/weather-averages/Germany/542451/Jena/571335/info.aspx Accessed 31 December 2011; World Weather Online, Leipzig Weather, Germany Weather Averages

http://www.worldweatheronline.com/Leipzig-weather-averages/Sachsen/DE.aspx Accessed 31 December 2011; World Weather Online, Berlin Weather, Germany Weather Averages

http://www.worldweatheronline.com/Berlin-weather/Berlin/DE.aspx Accessed 31 December 2011; World Meteorological Organization, World Weather Information Service, Weather Information for Leipzig http://worldweather.wmo.int/016/c01350.htm Accessed 31 December 2011; Hänsel S, Petzold S, Matschullat J (2007) Precipitation trend analysis for Central Eastern Germany. In: Střelcová K, Škvarenina J, Blaženec M (eds) Bioclimatology and natural hazards, International Scientific Conference, Poľana nad Detvou, Slovakia, September 17–20, 2007 Accessed http://cbks.cz/SbornikPolana07/pdf/Hansel_et_al.pdf; City Population Germany Thuringen http://www.citypopulation.de/Deutschland-Thuringen.html Accessed 31 December 2011

[4] US population figures are for the named metropolitan statistical areas. Population figures for Australia refer to the Melbourne and Adelaide statistical divisions and the Bendigo statistical district. Figures for Germany refer to the named cities.

astounding size of metropolitan areas would not be possible without modern forms of transportation and communication. Over the last century, technological innovation has overshadowed many of the earlier biophysical limitations to urbanization (Glaeser 2011). Characteristics of place once vital and integral to urban growth (such as water power, fertile soils, or a deep harbor) became less important as technological innovation found substitutes for these natural amenities, also known as ecosystem services. Limitations to urban growth could be overcome by engineered solutions, whether it was levees for flood-prone cities, DDT to eliminate mosquito populations, or air conditioners to allow comfortable living in the desert (Gober 2006). Urbanization models that developed in an era of rapid technological advances thus predicted growth and change using socio-economic data alone, treating the earth as a featureless plane, devoid of the vagaries of the natural environment, much like the famous concentric ring model developed by University of Chicago sociologists nearly a century ago (Burgess 1925).

Yet, even with continued technological development and expanded economic activity that dominate the farthest reaches of Earth's systems, the biophysical environment of cities is reemerging in urban theory as a limiting agent and a provider of life-sustaining ecosystem services. Hurricane Katrina along the Gulf Coast of the United States and the Black Saturday forest fires around Melbourne, Australia are clear reminders that urban areas cannot entirely shield themselves from natural disturbances, even in advanced, wealthy countries (Colten 2006; Chapin et al. 2010). Much of the ecological literature on ecosystem services and cities has highlighted negative effects of cities on ecosystem service provisioning, although recent perspectives include an understanding of the ecosystem benefits that well-planned cities can provide, particularly when compared with the alternative of sprawling settlements (Colding 2011; Gaston et al. 2010; McDonald and Marcotullio 2011). Increased attention to potential short and long-term consequences of global climate change has also brought into focus the need to better comprehend the challenges facing economic and ecological viability in ecosystems worldwide, including cities (Grimm et al. 2008a). For understanding the dynamics of metropolitan systems and addressing the urgency for sustainable solutions, ecology cannot be ignored in urbanization models (McKinney 2010; Newman and Jennings 2008; Colding 2011).

Coupled socio-ecological systems

It is no longer tenable to study cities as separate human artifacts divorced from the limitations or opportunities provided by the biophysical environment. Instead, urban ecologists and others conceive urban areas as coupled socio-ecological systems (Clucas and Marzluff 2011; Liu et al. 2007a, b; Warren et al. 2010; Zipperer et al. 2011). Several organizations have now adopted or promoted socio-ecological frameworks to guide future research endeavors, including the US Long Term Ecological Research network (Collins et al. 2011), the US National Science Foundation's Dynamics of Coupled Natural and Human Systems program and Science, Engineering and Education for Sustainability portfolio, the French National Center for Scientific Research (CNRS) Institute of Ecology and Environment, the international Resilience Alliance, and the International Human Dimensions Program's Global Land Project and the Urbanization and Global Environmental Change (UGEC) project. While they differ in terminology and emphases, these and other projects recognize that urban and other ecosystems can only be understood by studying the *interactions* between social and ecological structures and functions. Take the conceptual model of UGEC, for example (Fig. 1). This construct encapsulates the development of urban-environmental theory from one of examining unidirectional impact of human-dominated urban systems on surrounding biophysical and chemical systems (theme 1) to how those biophysical and chemical systems influence the urban environment, and finally how urban systems (consisting of biotic and abiotic components) and biophysical/chemical systems affect one another (themes 3 and 4) (Sanchez-Rodriguez et al. 2005).

These coupled socio-ecological frameworks help scientists understand how urban ecosystems function as complex, adaptive systems (Batty 2008). But rapid adoption of such

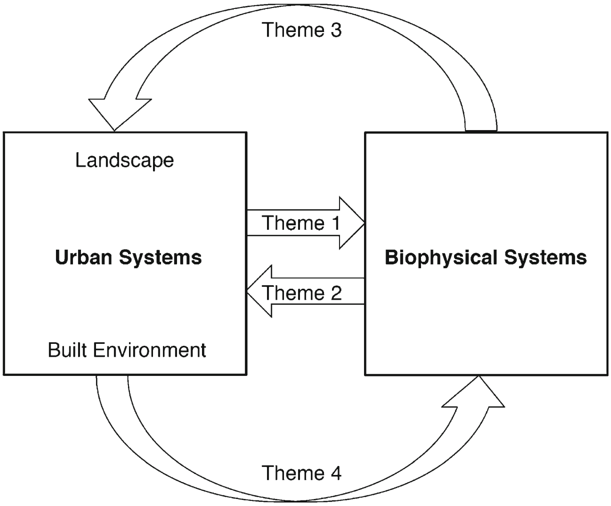

Fig. 1 Conceptual diagram of the Urbanization and Global Environmental Project. Theme 1 examines impacts of urban systems on biophysical systems. Research in theme 2 analyzes the role of the biophysical system in shaping urban systems. Theme 3 examines the feedbacks from the interaction of themes 1 and 2 on the social and ecological dynamics in urban systems. Theme 4 focuses on the feedbacks from theme 3 on the dynamics of biophysical systems. The progression of themes encapsulates the development of urban environmental theory from unidirectional impacts to integrated systems approaches. Source: (Sanchez-Rodriguez et al. 2005)

frameworks is also driven by policy needs of finding better, more sustainable ways to manage urbanization. Particularly in rapidly growing and water-limited environments, such as the US Southwest, governmental and non-governmental organizations are attempting to manage urban growth in ways that protect and maintain ecosystem services while maintaining healthy economies (Balsas 2008). One example is Indian Bend Wash in Scottsdale, Arizona. Designed primarily for flood control, this series of lakes and open space also provides recreation services, aquatic habitat, and hotspots for nitrogen cycling through a series of perennial lakes (Roach et al. 2008). As urbanization alters native ecosystems, urban planners design new ecosystems to replace some original functionality but also to cater to other services, such as recreation or attractive viewsheds, desired by urban residents (Pauleit et al. 2011; Sadler et al. 2010). The Central Arizona-Phoenix LTER project has consulted with developers in the greater Phoenix region about designed ecosystems that can deliver ecosystem services to nearby residents while reducing typical impacts of large tract developments. In greater Manchester, UK, policymakers and scientists are exploring the use of green infrastructure, particularly greenspace, to deal with increasing heat through global and local climate change as well as to create and restore habitat for bird species and other fauna and flora (Pauleit et al. 2011). Another example is the Tree and Shade Task Force of the City of Phoenix (2010), which is investigating how built infrastructure and vegetation can most effectively ameliorate the growing urban heat island in the region. This initiative has the potential to improve livability in the downtown core, an important consideration for attracting more residents and businesses to the central city, reduce vulnerability to extremes in temperature, and provide habitat for biota in areas previously dominated by asphalt and concrete (Harlan et al. 2006). Even brownfield sites, typically found in older industrial neighborhoods, can provide habitat for diverse species (Eyre et al. 2003). Rather than an eyesore, brownfields can be managed as an asset for biodiversity protection in urban areas (Kattwinkel et al. 2011). Shrinking cities such as Leipzig or Detroit, where populations are in decline, can also provide chances to bring open space and biodiversity into once dense urban cores (Haase 2008). Ecologically informed management is necessary for long-term sustainability of metropolitan systems (Colding 2011; McKinney 2010; McDonnell et al. 2009; Niemelä et al. 2011a; Stuart-Murray 2011).

Comparative gradient approach

Comparative approaches to examining the process of urbanization have enjoyed renewed interest over the last decade, in part related to debates about the presumed homogenizing effects of globalization (Kim and Short 2008; Dear 2005; Halle 2003; Soja 1992). While places will always have unique features, analyses across cities or "comparative urbanism," allows researchers to search for generalities, or "deep analogies," whether in urban form or processes (Nijman 2007b, p.4). Most observers search for similarities in structure or appearance of cities, but comparative urbanism also explores generalities in function. An advantage of focusing on function is that it can liberate researchers from explaining differences in form that are historically and geographically contingent (Nijman 2007a). Similarly, comparative urbanism need not be restricted to a particular point in time. Some scholars have argued that an examination of urbanism over very long periods, from ancient cities to the present, can illuminate what characteristics of cities or the urban experience are common, fundamental properties (Smith 2009). For example, neighborhoods, as a social and built-form organizing unit, appear in cities from ancient Mesopotamia to present-day megacities (Smith 2010). A challenge for contemporary comparative research is to recognize that cities are not discretely separate objects but are "open, embedded, and relational" (Ward 2008, p. 407), making the case for understanding the socioecological dynamics in regional city systems or megapolitan areas (Grimm et al. 2008b). For example, biophysically, modern cities all share an atmospheric pollution "footprint" that extends beyond their boundaries to an extent dictated by wealth, technology, and to some extent urban form (Luck et al. 2001; Grimm et al. 2008a). Recent comparative research has analyzed data from across cities to elucidate urban patterns and propose mathematical scaling rules as a predictive framework (Bettencourt and West 2010; Bettencourt et al. 2010).

Ecologists have also used comparative approaches to study the structure and composition of urban ecosystems. McDonnell and Hahs (2009) provide a useful typology and review of comparative approaches in urban ecology, which include urbanization gradients, rural–urban gradients, and research that examines change over time at single or multiple urban study sites. For example, research on urban amphibian assemblages in the Greater Melbourne area used a rural–urban gradient approach to test the applicability of metacommunity theory to urban ecosystems (Parris 2006). Similarly, researchers have examined carabid beetle assemblages across rural–urban gradients in several cities globally through the GLOBENET project (Niemelä et al. 2002, 2009; Niemelä and Kotze 2009) and herpetofauna communities along a wildland-urban riparian gradient (Banville and Bateman 2012). Other studies have sought to understand ecological patterns and processes across multiple urban areas, including work on plant extinction rates across 22 cities of varying ages around the world (Hahs et al. 2009b); a study analyzing biodiversity in neighborhoods across five metropolitan areas globally (Turner et al. 2004); and research examining the richness and occurrence of Anuran species across nine urban areas in southeastern Australia (Smallbone et al. 2011). Using socio-economic and vegetation data for the same nine urban areas, Luck et al. (2009) examined the relationship between neighborhood socioeconomic characteristics and vegetation change over time.

McDonnell and Hahs (2009, p. 73) suggest that the integration of these ecological approaches with comparative social science approaches will lead to "the development of a more robust comparative ecology of cities" and ultimately the creation of the knowledge base necessary to design sustainable cities. Gradients have been used for more than a century in the social and ecological sciences. Scholars have used gradients to explain differences in land values (von Thünen 1966[1826]), social structure (Park et al. 1925), land use (Christaller 1933 [1966]), species distributions (Whittaker 1967), soil properties (Jenny 1941), ecosystem function (Vitousek 2004), and more recently the abundance and diversity of organisms in and around urban areas (McDonnell and Hahs 2008). In the Baltimore Ecosystem Study, the rural–urban gradient in the Gwynns Falls Watershed provides a 'natural experiment' of the effects of urbanization on ecosystem structure and function (Pickett and Cadenasso 2006). Location along the rural–urban gradient can in essence substitute for time and help to predict the effects of encroaching urban and suburban growth on ecosystems (Carreiro and Tripler 2005). Evidence also suggests that land values and uses follow a bid-rent gradient where highest land values and uses are found in the Phoenix central business district and decline with distance from the center (Keys, Wentz and Redman 2007). Both from an ecological and social science perspective, the degree of urban-*ness* makes a difference to structure and function, or patterns and processes, of urban environments.

Most urban research on gradients has focused on changes within urban areas or regions. However, cities themselves can be arranged into gradients along a variety of spatial, social, economic, and biophysical dimensions, such as population, water use, or pollutants emitted. As other researchers (Bettencourt and West 2010; Bettencourt et al. 2010) have suggested, gradients or hierarchies may allow us to tease out relationships between urban form, pattern, and function. Rather than focus on a single city, we see value in comparing multiple cities across both social and biophysical characteristics (Table 1) (see also Grimm et al. 2008b). Similar to the natural experiment approach of the Baltimore Ecosystem Study's rural–urban gradient, a gradient of cities may be a useful way to predict how a large metropolitan region like Phoenix might foreshadow the social and ecological dynamics of smaller, nearby cities such as Albuquerque, New Mexico or Las Cruces, New Mexico. All three are in an arid region with moderate winter temperatures and hot summers, rely heavily on imported surface water for irrigated agriculture and other uses, are characterized by rapid population growth and low-density development on the fringe, and are surrounded by large tracts of public and Native American land. All benefited from federal investment, especially defense, and boomed in population during and after the Second World War. Large land sales of State Trust Land (Phoenix) and Bureau of Land Management holdings (Las Cruces) enable rapid and typically large scale development, while Pueblos (Albuquerque), Indian Communities (Phoenix), and Forest Service and National Park Service lands that surround all three cities restrict growth, resulting in the leap-frog patterns of urbanization (York et al. 2011).

Gradients are also useful for testing the relationships between city size – defined by such factors as population, spatial extent, energy and material flows, financial and human capital – and socio-ecological dynamics while holding the biophysical environment relatively constant. For instance, how might the urban ecosystems of Melbourne or Berlin (pop. ~4 million), differ in structure and function from the medium-sized (pop. ~ 1 million) Adelaide or Leipzig? A comparative gradient approach also permits a corollary exercise of examining key differences in socio-ecological dynamics, and how they relate to place-specific, historical, or institutional factors. Analyses across regional gradients of metropolitan areas will allow researchers to elucidate patterns and processes of urbanization across time and space and their effect on the urban socio-ecological system. A series of hypotheses that flow from this approach are outlined below.

Hypotheses

Hypothesis 1: The current size, configuration, and function of larger metropolitan ecosystems predicts the potential trajectory of smaller urban areas Research suggests that urban scale matters. City size is a major determinant of many urban characteristics, and cities are fractal, scaled versions of one another (Bettencourt and West 2010). This hypothesis can be tested with longitudinal studies into the future, but may also be tested retrospectively. For instance, in 1960, Phoenix roughly matched the current population of Albuquerque. One can test the hypothesis by measuring similarities (or differences) in physical extent, configuration (e.g., fragmentation of land use) and function (e.g., agricultural to non-agricultural production).

Hypothesis 2: Timing of growth explains the greatest variance in urban ecosystem structure and function This hypothesis is derived from the notion that timing is fundamental and that historical trajectories have a strong bearing on city form and function (Abu-Lughod 1991). In essence, it expresses the opposite of Hypothesis 1. Thus, Adelaide will never be similar to Melbourne, or Bendigo like Adelaide, because the context and drivers of time periods trump all else in generating urban ecosystems. For instance, even though Melbourne in 1940 matched the population of Adelaide in 2010, the economy, technology, and even social norms of 1940 created an urban ecosystem that is vastly different from any in the present. However, it is possible that timing of growth has steps and plateaus in terms of how it affects ecosystem function. The period following the Second World War, for example, had a much greater impact on urbanization, especially sub-urbanization, than the pre-war era in Australia and other wealthy countries. For most of the twentieth century, urbanization in China was slow or stagnant but that region has seen explosive growth in urban populations and megacities over the last two decades (Seto et al. 2010). Had China's urbanization rate accelerated in the early 20th rather than 21st century, its cities would likely have looked and functioned in decidedly different ways than they do now. Segmenting metropolitan areas by age of development would be one mechanism for testing the effects of timing on the structure and function of urban ecosystems. Studies from Baltimore, for instance, show that age of housing—a proxy for neighborhood age—is a good predictor of vegetation cover (Troy et al. 2007).

Hypothesis 3: Form and function of urban ecosystems are converging over time Globalization and commercialization of economies may homogenize the function and appearance of urban areas, especially for global cities (Sassen 2008). Many commentators have remarked on how national retail and restaurants chains as well as national models of residential development have homogenized urban landscapes, making one indistinct from another. The result is a sense of 'placelessness' (Relph 1987) or a 'geography of nowhere' (Kunstler 1993). In ecology, the urban ecosystem convergence hypothesis suggests that ecosystem properties and functioning within and between cities are similar despite the disparate characteristics of each city's surrounding native ecosystem (Pouyat et al. 2003; Grimm et al. 2008b). Additionally, social behaviors, such as maintaining and fertilizing lawns despite knowledge of the economic and environmental costs (Robbins 2007), play an important role in homogenizing the ecological properties of cities. Proliferation of large, national retail stores with standard nursery stock may also play a role in homogenizing landscapes, controlling biodiversity patterns of residential landscapes (Walker et al. 2009). The GLOBENET project comparing carabid beetle assemblages across several cities globally (Niemelä et al. 2002, 2009; Niemelä and Kotze 2009) and work on soil organic carbon in cities (Pouyat et al. 2009) are examples of how to test the convergence hypothesis.

Hypothesis 4: Urban ecosystems become more socially segregated and ecologically fragmented as city populations increase As populations of cities grow, socioeconomic groups tend to become more spatially segregated. One study in the United States, for example, found that a 10 % increase in population leads to a 5 % increase in spatial segregation (Jargowski 1996). Data from the US Census Bureau (http://www.census.gov/hhes/www/housing/housing_patterns/ch5.html) also show that larger cities have higher rates of segregation than medium and smaller cities. An examination of segregation in Australia, New Zealand, the United States, Canada, and the United Kingdom, shows that cities with large populations generally have higher rates of segregation than smaller cities (Johnston et al. 2007). We hypothesize that larger cities will lead to greater fragmentation of ecological structure. If social characteristics are a driver of land management (Hope et al. 2003; Grove et al. 2006), then it is possible that higher degrees of social segregation in large cities are also associated with fragmentation of urban ecosystem structure (e.g., vegetation cover or diversity).

Hypothesis 5: Larger cities are more innovative in managing urban ecosystems Using patent data, scholars have shown that larger cities are more innovative than smaller cities, and that innovation scales at a rate faster than population growth (Bettencourt et al. 2007; 2010). We hypothesize that such scaling laws also apply to innovation in management of urban ecosystems. The hypothesis can be tested using indicators that rank cities in terms of implementation of new programs or initiatives that are targeted at urban ecosystem management. These methods have been successfully applied to the cognate exercise of measuring degree of sustainability across metropolitan areas (Portney 2003).

Conclusions

Grand challenges of the urban century – such as global climate change, enduring poverty, and threats to biodiversity – punctuate the need for urban theory, currently dominated by socioeconomic principles, to incorporate ecological theory. At the same time, urban ecology needs a coherent theory or framework in order to address these grand challenges and contribute to urban sustainability (Niemelä et al. 2011b). A socio-ecological framework that encapsulates theory from the social and ecological sciences will improve understanding of metropolitan dynamics and open up possibilities for improved, sustainable management of urban ecosystems (Alberti 2008; Alberti and Marzluff 2004; Douglas 2011; Newman and Jennings 2008; Niemelä et al. 2011a). In addition to a socio-ecological framework, we argue that the use of a comparative approach can strengthen understanding and management of urban ecosystems. Studying Albuquerque or Adelaide or Addis Ababa in isolation, even using a socio-ecological framework, can take us only so far in our comprehension and management of urban ecosystems. Systematic comparative urban research across regions and globally, driven by questions or hypotheses such as those offered in this paper, is a critical and important next step in urban ecology (Hahs et al. 2009a). However, comparisons must be bound by some common denominators, such as the biophysical, social, and historical commonalities of regions.

A regional context may provide a sound basis for comparative research, but we also suggest that a gradient approach is a useful mechanism for comparison. Differing magnitudes, densities, and extents of social and ecological variables between cities that share some common characteristics allow researchers and managers to understand the role of key drivers in the dynamics of urban ecosystems. Testing the convergence hypothesis, for instance, would be more problematic if we compared Melbourne to Moscow rather than Melbourne to Adelaide, because Australian cities have some common social and biophysical characteristics that act, in essence, as controls. By selecting cities that fall on a gradient with underlying common features, we can test and isolate the impact of differences in population and wealth, for instance, on convergence because we have fewer confounding factors. The second value of a gradient approach is the ability to substitute differences for time. In the southwestern United States, Las Cruces has the opportunity to learn from the experiences, failures, and successes of Albuquerque just as Albuquerque can learn from Phoenix. In this regard, a comparative gradient approach has real value in advancing theory in urban ecology and providing useful scenarios for sustainable management of metropolitan areas.

Acknowledgements This work was supported by a USDA Forest Service Joint Venture Agreement (08-JV-11221632-260), and by the National Science Foundation under awards BCS-1026865 Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER), and BCS-0948749 ULTRA-Ex: Land- and Water-Use Decision Making and Ecosystem Services along a Southwestern Socioecological Gradient.

References

Abu-Lughod J (1991) New York, Chicago, Los Angeles: America's global cities. University of Minnesota Press, Minneapolis

Alberti M (2008) Advances in urban ecology: Integrating humans and ecological processes in urban ecosystems. Springer, New York

Alberti M, Marzluff JM (2004) Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. Urban Ecosystems 7:241–265

Balsas C (2008) Sustainable urban regeneration in Phoenix, Arizona: Implications for multi-dimensional governance. In: Kidokoro T, Harata N, Subanu LP, Jessen J, Motte A, Seltzer EP (eds) Sustainable city regions: Space, place and governance. Springer, Hicom

Banville MJ, Bateman H (2012) Urban and wildland herpetofauna communities and riparian microhabitats along the Salt River, Arizona. Urban Ecosystems. doi:10.1007/s11252-012-0228-5

Batty M (2008) The size, scale, and shape of cities. Science 319:769–771

Berry BJL (1991) Long-wave rhythms in economic development and political behavior. Johns Hopkins University Press, Baltimore

Bettencourt L, West G (2010) A unified theory of urban living. Nature 467:912–913

Bettencourt L, Lobo J, Helbing D, Kuhnert C, West G (2007) Growth, innovation, scaling, and the pace of life in cities. Proc Natl Acad Sci 104:7301

Bettencourt LMA, Lobo J, Strumsky D, West GB (2010) Urban scaling and its deviations: Revealing the structure of wealth, innovation and crime across cities. PLoS One 5(11):1–9

Burgess EW (1925) The growth of the city. In: Park R, Burgess E, McKenzie RD (eds) The City: Suggestions for the study of human nature in the urban environment. University of Chicago Press, Chicago

Carreiro MM, Tripler CE (2005) Forest remnants along urban–rural gradients: Examining their potential for global change research. Ecosystems 8(5):568–582

Chapin FS III, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, Olsson P, Smith DMS, Walker B, Young OR, Berkes F, Biggs R, Grove JM, Naylor RL, Pinkerton E, Steffen W, Swanson FJ (2010) Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. Trends in Ecology & Evolution 25(4):241–249

Christaller W (1933) Die zentralen orte in Suddeutschland. Gustav Fischer, Jena, Germany. Translated by Baskin CW (1966) as Central places in Southern Germany. Prentice Hall, New York

City of Phoenix (2010) Tree and shade master plan. http://phoenix.gov/PARKS/shade52010.pdf Accessed 27 August 2010

Clucas B, Marzluff JM (2011) Coupled relationships between humans and other organisms in urban areas. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 135–147

Colding J (2011) The role of ecosystem services in contemporary urban planning. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 228–237

Collins SL, Carpenter SR, Swinton SM, Orenstein DE, Childers D, Gragson TL, Grimm NB, Grove JM, Harlan SL, Kaye JP, Knapp AK, Kofinas GP, Maguson JJ, McDowell WH, Melack JM, Ogden LA, Robertson P, Smith MD, Whitmer AC (2011) An integrated conceptual framework for long-term ecological research. Front Ecol Environ. doi:10.1890/100068
Colten CE (2006) An unnatural metropolis: Wresting New Orleans from nature. Louisiana State University Press, Baton Rouge
Dear M (2005) Comparative urbanism. Urban Geography 26(3):247–251
Douglas I (2011) The analysis of cities as ecosystems. In: Douglas I, Goode D, Houck M, Wang R (eds) The Routledge handbook of urban ecology. Routledge, New York, pp 17–25
Eyre MD, Luff ML, Woodward JC (2003) Beetles (Coleoptera) on brownfield sites in England: An important conservation resource? Journal of Insect Conservation 7(4):223–231
Gaston KJ, Davies ZG, Edmondson JL (2010) Urban environments and ecosystem functions. In: Gaston KJ (ed) Urban ecology. Cambridge University Press, Cambridge, pp 35–52
Glaeser E (2011) Triumph of the city: How our greatest invention makes us richer, smarter, greener, healthier, and happier. The Penguin Press, New York
Gober P (2006) Metropolitan Phoenix: Place making and community building in the desert. University of Pennsylvania Press, Philadelphia
Grimm NB, Grove JM, Pickett ST, Redman CL (2000) Integrated approaches to long-term studies of urban ecological systems: The conceptual basis for studying urban ecological systems. BioScience 50:571–584
Grimm NB, Faeth S, Golubiewski N, Redman C, Wu JW, Bai X, Briggs JM (2008a) Global change and the ecology of cities. Science 319:756–760
Grimm NB, Foster D, Groffman P, Grove JM, Hopkinson CS, Nadelhoffer K, Peters D, Pataki DE (2008b) The changing landscape: Ecosystem responses to urbanization and pollution across climatic and societal gradients. Front Ecol Environ 6:264–272
Grove JM, Troy AR, O'Neil-Dunne JPM, Burch WR, Cadenasso ML, Pickett STA (2006) Characterization of households and its implications for the vegetation of urban ecosystems. Ecosystems 9:578–597
Haase D (2008) Urban ecology of shrinking cities: An unrecognized opportunity? Nature and Culure 3:1–8
Hahs AK, McDonnell MJ, Breuste J (2009a) A comparative ecology of cities and towns: Synthesis of opportunities and limitations. In: McDonnell MJ, Hahs AK, Breuste JH (eds) Ecology of cities and towns: A comparative approach. Cambridge University Press, Cambridge, pp 574–596
Hahs AK, McDonnell MJ, McCarthy MA, Vesk PA, Corlett RT, Norton BA, Clements SE, Duncan RP, Thompson K, Schwartz MW, Williams NSG (2009b) A global synthesis of plant extinction rates in urban areas. Ecol Lett 12:1165–1173
Halle D (2003) New York and Los Angeles: Politics, society, and culture, a comparative view. The University of Chicago Press, Chicago
Harlan SL, Brazel AJ, Prashad L, Stefanov WL, Larsen L (2006) Neighborhood microclimates and vulnerability to heat stress. Social Science and Medicine 163(11):2847–2863
Hope D, Gries C, Zhu W, Fagan WF, Redman CL, Grimm NB, Nelson AL, Martin C, Kinzig A (2003) Socioeconomics Drive Urban Plant Diversity. PNAS 100:8788–8792.
Jargowski PA (1996) Poverty and place: Ghettos, barrios and the American city. Russell Sage, New York
Jenny H (1941) Factors of soil formation: A system of quantitative pedology. McGraw Hill Book Company, New York
Johnston R, Poulsen M, Forrest J (2007) The geography of ethnic residential segregation: A comparative study of five countries. Ann Assoc Am Geogr 97(4):713–738
Kattwinkel M, Biedermann R, Kleyer M (2011) Temporary conservation for urban biodiversity. Biol Conserv 144(9):2335–2343
Keys E, Wentz E, Redman C (2007) The spatial structure of land use from 1970–2000 in the Phoenix, Arizona, metropolitan area. Prof Geogr 59:131–147
Kim Y, Short J (2008) Cities and economies. Routledge, New York
Knox PL (2008) Metroburbia. Rutgers University Press, Piscataway
Kunstler JH (1993) The geography of nowhere: The rise and decline of America's man-made landscape. Simon and Schuster, New York
Liu J, Dietz T, Carpenter SR, Alberti MR, Folke CR, Moran ER, Pell AN, Deadman PN, Kratz TN, Lubchenco JN, Ostrom EN, Ouyang ZN, Provencher WN, Redman CL, Schneider SH, Taylor WW (2007a) Coupled human and natural systems. Ambio 36:639–649
Liu J, Dietz T, Carpenter SR, Alberti MR, Folke CR, Moran ER, Pell AN, Deadman PN, Kratz TN, Lubchenco JN, Ostrom EN, Ouyang ZN, Provencher WN, Redman CL, Schneider SH, Taylor WW (2007b) Complexity of coupled human and natural systems. Science 317:1513–1516
Luck M, Jenerette GD, Wu J, Grimm NB (2001) The urban funnel model and spatially heterogeneous ecological footprint. Ecosystems 4:782–796

Luck G, Smallbone L, O'Brien R (2009) Socio-economics and vegetation change in urban ecosystems: Patterns in space and time. Ecosystems 12:604–620
McDonald R, Marcotullio P (2011) Global effects of urbanization on ecosystem services. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 193–205
McDonnell MJ, Hahs AK (2008) The use of gradient analysis studies in advancing our understanding of the ecology of urbanizing landscapes: Current status and future directions. Landsc Ecol 23:1143–1155
McDonnell MJ, Hahs AK (2009) Comparative ecology of cities and towns: Past, present, and future. In: McDonnell MJ, Hahs AK, Breuste JH (eds) Ecology of cities and towns: A comparative approach. Cambridge University Press, Cambridge
McDonnell MJ, Breuste JH, Hahs A (2009) Introduction: Scope of the book and need for developing a comparative approach to the ecological study of cities and towns. In: McDonnell MJ, Hahs AK, Breuste JH (eds) Ecology of cities and towns: A comparative approach. Cambridge University Press, Cambridge, pp 1–6
McKinney M (2010) Urban futures. In: Gaston K (ed) Urban ecology. Cambridge University Press, Cambridge, pp 287–308
Melosi MV (2005) Path dependence and urban history: Is a marriage possible? In: Schott D, Luckin B, Massard-Guilbaud G (eds) Resources of the city: Contributions to an environmental history of modern Europe. Ashgate, Burlington, pp 262–275
Newman P, Jennings I (2008) Cities as sustainable ecosystems: Principles and practices. Island Press, Washington, D.C
Niemelä J, Kotze DJ (2009) Carabid beetle assemblages along urban to rural gradients: A review. Landscape and Urban Planning 92(2):65–71
Niemelä J, Kotze DJ, Venn S, Penev L, Stoyanov I, Spence J, Hartley D, Montes de Oca E (2002) Carabid beetle assemblages (Coleoptera, Carabidae) across urban–rural gradients: An international comparison. Landsc Ecol 17:387–401
Niemelä J, Kotze DJ, Yli-Pelkonen V (2009) Comparative urban ecology: Challenges and possibilities. In: McDonnell MJ, Hahs AK, Breuste JH (eds) Ecology of cities and towns: A comparative approach. Cambridge University Press, Cambridge, pp 9–24
Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) (2011a) Urban ecology. Oxford University Press, Oxford
Niemelä J, Breuste J, Elmqvist T, Guntenspergen G, James P, McIntyre N (2011b) Concluding remarks: The way forward for urban ecology. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 319–321
Niemelä J, Breuste J, Elmqvist T, Guntenspergen G, James P, McIntyre N (2011c) Introduction. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 1–4
Nijman J (2007a) Introduction – Comparative urbanism. Urban Geography 28:1–6
Nijman J (2007b) Place-particularity and "deep analogies": A comparative essay on Miami's rise as a world city. Urban Geography 28:92–107
Park R, Burgess E, McKenzie RD (1925) The city: Suggestions for the study of human nature in the urban environment. University of Chicago Press, Chicago
Parris KM (2006) Urban amphibian assemblages as metacommunities. J Anim Ecol 75(3):757–764
Pauleit S, Liu L, Ahern J, Kazmierczak A (2011) Multifunctional green infrastructure planning to promote ecological services in the city. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 272–286
Pickett STA, Cadenasso ML (2006) Advancing urban ecological studies: Frameworks, concepts, and results from the Baltimore Ecosystem Study. Austral Ecology 31:114–125
Pickett ST, Cadenasso ML, Grove JM, Groffman PM, Band LE, Boone CG, Burch WR Jr, Grimmond SB, Hom J, Jenkins JC, Law NL, Nilon CH, Pouyat RV, Szlavecz K, Warren PS, Wilson MA (2008) Beyond urban legends: An emerging framework of urban ecology, as illustrated by the Baltimore Ecosystem Study. BioScience 58:139–150
Portney KE (2003) Taking sustainable cities seriously: Economic development, the environment, and quality of life in American cities. MIT Press, Cambridge
Pouyat RV, Russell-Anelli J, Yesilonis ID, Groffman PM (2003) Soil carbon in urban forest ecosystems. In: Kimble JM, Heath LS, Birdsey RA, Lal R (eds) The potential of US forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, Boca Raton
Pouyat RV, Yesilonis ID, Golubiewski NE (2009) A comparison of soil organic carbon stocks between residential turf grass and native soil. Urban Ecosystems 12:45–62
Relph E (1987) The modern urban landscape. The Johns Hopkins University Press, Baltimore

Roach J, Heffernan JB, Grimm NB, Arrowsmith JR, Eisinger C, Rychener T (2008) Unintended consequences of urbanization for aquatic ecosystems: A case study from the Arizona desert. BioScience 58:715–727
Robbins P (2007) Lawn people: How grasses, weeds, and chemicals make us who we are. Temple University Press, Philadelphia
Sadler J, Bates A, Hale J, James P (2010) Bringing cities alive: The importance of urban green spaces for people and biodiversity. In: Gaston K (ed) Urban ecology. Cambridge University Press, Cambridge, pp 230–260
Sanchez-Rodriguez R, Seto KC, Simon D, Solecki WD, Kraas F, Laumann G (2005) Science plan: Urbanization and global environmental change. Urbanization and Global Environmental Change Project, Bonn http://ugec.asu.edu/files/UrbanizationSciencePlan.pdf Accessed 29 June 2010.
Sassen S (2001) The global city. Princeton University Press, Princeton
Sassen S (2008) Re-assembling the urban. Urban Geography 29:113–126
Seto KC, Sánchez-Rodríguez R, Fragkias M (2010) The new geography of contemporary urbanization and the environment. Annu Rev Environ Resour 35(1):167–194
Short JR (2006) Urban theory: A critical assessment. Palgrave MacMillan, New York
Smallbone LT, Luck GW, Wassens S (2011) Anuran species in urban landscapes: Relationships with biophysical, built environment and socio-economic factors. Landscape and Urban Planning 101:43–51
Smith ME (2009) Editorial – Just how comparative is comparative urban geography? A perspective from archaeology. Urban Geography 30:113–117
Smith ME (2010) The archaeological study of neighborhoods and districts in ancient cities. J Anthropol Archaeol 29:137–154
Soja E (1992) The stimulus of a little confusion: A contemporary comparison of Amsterdam and Los Angeles. In: Smith MP (ed) After modernism: Global restructuring and the changing boundaries of city life. Transaction Publishers, New Brunswick
Stuart-Murray J (2011) Making urban ecology a key element in urban development and planning. In: Douglas I, Goode D, Houck M, Wang R (eds) The Routledge handbook of urban ecology. Routledge, New York, pp 630–635
Troy AR, Grove JM, O'Neil-Dunne JPM, Pickett STA, Cadenasso ML (2007) Predicting opportunities for greening and patterns of vegetation on private urban lands. Environ Manag 40(3):394–412
Turner WR, Nakamura T, Dinetti M (2004) Global urbanization and the separation of humans from nature. BioScience 54:585–590
Vitousek PM (2004) Nutrient cycling and limitation: Hawai'i as a model system. Princeton University Press, Princeton
Von Thunen JH, Hall PG (1966) Isolated state: An English edition of *Der isolierte Staat*. Pergamon Press, Oxford
Walker JS, Grimm NB, Briggs JM, Gries C, Dugan L (2009) Effects of urbanization on plant species diversity in central Arizona. Front Ecol Environ 7:465–470
Ward K (2008) Toward a comparative (re)turn in urban studies? Some reflections. Urban Geography 29 (5):405–410
Warren PS, Harlan S, Boone C, Lerman SB, Shochat E, Kinzig AP (2010) Urban ecology and human social organization. In: Gaston K (ed) Urban ecology. Cambridge University Press, Cambridge, pp 172–201
Whittaker RH (1967) Gradient analysis of vegetation. Biological Reviews of the Cambridge Philosophical Society 42: 207
York A, Shrestha M, Boone CG, Zhang S, Harrington J, Prebyl T, Swann A, Agar M, Antolin M, Nolen B, Wright J, Skaggs R (2011) Land fragmentation under rapid urbanization: A cross-site analysis of Southwestern cities. Urban Ecosystems 14(3):429–455
Zipperer WC, Morse WC, Gaither CJ (2011) Linking social and ecological systems. In: Niemelä J, Breuste J, Guntenspergen G, McIntyre NE, Elmqvist T, James P (eds) Urban ecology. Oxford University Press, Oxford, pp 298–308