The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients

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Urbanization, an important driver of climate change and pollution, alters both biotic and abiotic ecosystem properties within, surrounding, and even at great distances from urban areas. As a result, research challenges and environmental problems must be tackled at local, regional, and global scales. Ecosystem responses to land change are complex and interacting, occurring on all spatial and temporal scales as a consequence of connectivity of resources, energy, and information among social, physical, and biological systems. We propose six hypotheses about local to continental effects of urbanization and pollution, and an operational research approach to test them. This approach focuses on analysis of "megapolitan" areas that have emerged across North America, but also includes diverse wildland-to-urban gradients and spatially continuous coverage of land change. Concerted and coordinated monitoring of land change and accompanying ecosystem responses, coupled with simulation models, will permit robust forecasts of how land change and human settlement patterns will alter ecosystem services and resource utilization across the North American continent. This, in turn, can be applied globally.

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Beyond climate, land use – and its manifestation as land-cover change and pollution loading – is the major factor altering the structure, function, and dynamics of Earth's terrestrial and aquatic ecosystems. Urbanization, in particular, fundamentally alters both biotic and abiotic ecosystem properties within, surrounding, and even at great distances from urban areas (Grimm *et al.* 2008). Around the world, rates of land change will increase greatly over the next 20–50 years, as human populations continue to grow and migrate (Alig *et al.* 2004; Theobald 2005). The nature, pattern, pace, and ecological and societal consequences of land change will vary on all spatial scales as a result of spatial variation in human preferences, economic and political pressures, and environmental sensitivities (Carpenter *et al.* 2007). To respond, we must determine how variables influence land change and ecosystem properties at multiple interacting scales, and understand feedbacks to human behavior.

Human social and economic activities drive land change at all scales, and may enhance or hinder the movement of materials via wind, water, and biological and social vectors, sometimes in surprising ways that cut across scales (Kareiva *et al.* 2007; Peters *et al.* [2008] in this issue). For example, individual human decisions can influence regional dynamics within a continent when many people respond similarly to the same economic or climatic driver; the Dust Bowl in the North American prairies during the 1930s is a historical example of such cumulative effects (Peters *et al.* 2004). Individual decisions can also influence broad-scale land-change dynamics on other continents; for example, a switch to soybean production in South America is being driven by market demand from China. In turn, the changes wrought by humans produce ecosystem dynamics that feed back to influence resource availability and human well-being. Human responses may ameliorate or exacerbate these effects. Thus, there are complex interactions and feedbacks between the direct manifestations of human activ-

In a nutshell:

- Land changes associated with urbanization drive climate change and pollution, which alter properties of ecosystems at local, regional, and continental scales
- Urbanization alters connectivity of resources, energy, and information among social, physical, and biological systems
- A continental research program across multiple gradients, within and radiating out from both small and large cities, is needed to advance understanding of urbanization beyond individual case studies
- Research should include spatially continuous information on land-cover change, monitoring of land change and accompanying ecosystem responses, and development of simulation models capable of producing robust forecasts of land change
- Forecasting land change will show how changing human settlement patterns alter ecosystem services and resource utilization at the continental scale

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ity and their diverse ecological consequences, across a range of interacting spatial and temporal scales (Figure 1).

Here, we consider land change (especially urbanization) and pollution arising from human activities. Ecosystem responses to these "press" events (ie continual or increasing stresses on ecosystems over relatively long time frames) occur on local, regional, and continental scales, as a consequence of connectivity among resources, energy, and information in social, physical, and biological systems (Peters *et al.* [2008] in this issue; Figure 1). For example, urban areas are both sources and recipients of atmospheric and aquatic pollutants. Eastern landscapes of the US receive depositions of air pollutants from the industrial Midwest, and small streams across the country receive pollutant loads (eg nitrate, ammonium) from intensive agriculture and concentrated feedlots (Mulholland *et al.* 2008). Meanwhile, the entire continent receives particulate and chemical inputs, borne in the upper atmosphere from distant global sources, including China and northern Africa(http://visibleearth.nasa.gov/view_set.php?categoryID=4831). Urban areas are also foci for species introductions (Hope *et al.* 2003; Crowl *et al.* [2008] in this issue).

There are many important two-way interactions between urban processes and climate that further complicate responses at multiple scales. The specter of sea-level rise and more frequent and severe hurricanes resulting from regional and global climate change is particularly important for urban ecosystems, as they tend to be located near coastlines (Crossett *et al.* 2004; Hopkinson et al. [2008] in this issue; WebFigure 1). Locally, changes in albedo, evapotranspiration, and surface energy balance in developed areas may exacerbate global warming through urban heat island and oasis effects (Arnfield 2003; Kalnay and Cai 2003). Dust generation from construction within urbanizing areas may be enhanced by drought. These urban dynamics may contribute to meso-scale and global climate change, through massive greenhouse-gas emissions and radiative forcing of non-greenhouse gases (Pielke *et al.* 2002), and by alteration of rainfall patterns (Cerveny and Balling 1998). Profound structural modification of streams and rivers, coupled with changes in impervious surfaces, affect hydro-ecology in, and downstream from, cities and suburbs (Paul and Meyer 2001).

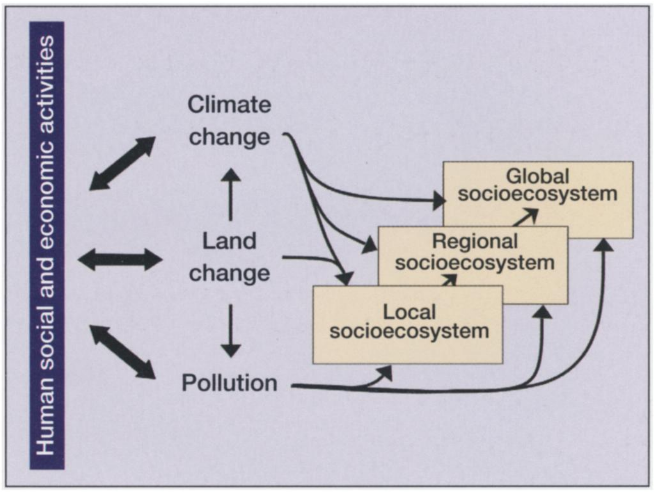


Figure 1. *Interactions among land change, climate change, and pollution, driven by human social and economic activities, in affecting local, regional, and global socioecosystems.*

Panel 1. Key research questions to guide development of continental and regional observation networks for understanding the interactions of urbanization, pollution, and climate change

- Q1: What are the ecological and socio-ecological consequences of local land-use changes at regional and continental scales?
- Q2: Does urbanization increase or decrease social, physical, and biological connectivity at local, regional, and continental scales?
- Q3: How will varying patterns of urbanization interact with climate change across continental gradients in climate and land cover to affect ecosystem processes and services?
- Q4: How are pollutant source and deposition regions (connected through air and water vectors) related to patterns of land use, and how do ecosystem structure, function, and services respond to changes in pollutant loadings resulting from changing land use?

The goals of this review are: (1) to demonstrate that interactions among component parts of landscapes (eg urban, rural, wildland), and interactions across scales from local to continental, are mediated by vectors of water, wind, organisms, and people, and (2) to provide an operational framework for conducting continental-scale research on land change and pollution in social–ecological systems. Key scientific questions that can be addressed by this framework relate to the ecological consequences of land change and human–environment dynamics, both as drivers and responders, as well as the origins and fates of pollutants at multiple, interacting scales (Panel 1).

■ Urbanization and pollution at the continental scale

Regional variation in ecosystems arises as a result of different combinations of climate, vegetation, and geomorphology. Both today and over the course of human history in North America, this variation is perceived and responded to by people who make choices about where to settle and how to use the land. There are therefore recognizable regional differences in settlement density, current types and intensities of land use, land-use legacies, and rates and patterns of urban–suburban growth (Figure 2; WebFigure 1). As a further consequence of these continental-scale differences, diffuse, "non-point" pollution coalesces into distinct hotspots or source regions, such as large urban agglomerations (or megapolitan areas; Panel 2; Figure 3) or zones of intensive agriculture (eg Figure 4).

In addition to the background template of natural systems, economic and cultural drivers influence human settlement patterns. The first wave of European settlers migrating across North America brought introduced Eurasian species and agricultural methods, initiating conti-

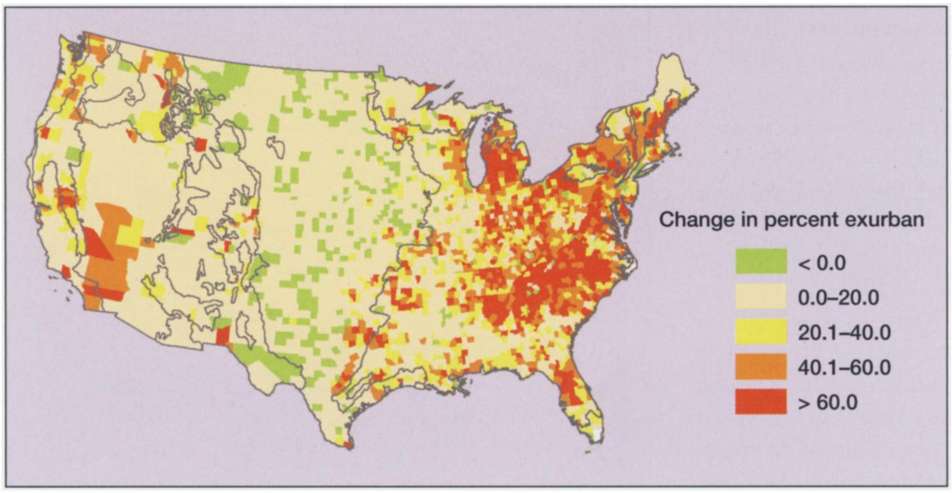


Figure 2. *Percentage change in exurban land use (defined as housing density of between 0.06 and 2.5 units ha^{-1}), between 1950 and 2000. From Brown* et al. *(2005).*

nent-wide ecological transformations. Today, the Southwest is a particularly important recipient region for Mexican immigrants, owing to geographical proximity and cultural and environmental similarities. Over the past century, the upper Midwest has been a magnet for northern Europeans, due to historical timing and the similarity of the region to these immigrants' native lands and climate.

Given biophysical and social influences on urbanization, ecosystem responses are likely to exhibit regional differences (see Panel 2). Classifying urbanizing regions based on both social and biogeophysical variables could form the basis for continental-scale comparisons of urbanization and resulting ecosystem responses. We expect that the nature and strength of feedbacks among urban–suburban land-use change and ecosystem biogeochemistry, hydroecology, and biodiversity will vary across the climatic, societal, and ecological settings that characterize these strongly contrasting regions.

Understanding atmospheric and aquatic transport processes and pollution generation has given atmospheric and aquatic scientists a strong working knowledge of the patterns of pollutant distribution at continental and sub-continental scales (eg Figures 2, 3). Yet, the ability to predict how connectivity across widely separated regions will lead to ecosystem responses to these patterns hinges upon a coordinated observation network distributed across pollutant gradients, coupled with experiments to identify mechanisms. At the continental scale, two hypotheses could be tested with such a network.

> ***Hypothesis 1.*** *Human sociodemographic changes are the primary drivers of land-use change, urbanization, and pollution at continental and sub-continental scales; in turn, these patterns are influenced by a continental template of climate and geography.*

We expect major land-use changes associated with urbanization and suburbanization, leading to spatial redistribution and transformation of energy and material resources. These changes include both the agglomeration of major US cities into megapolitan regions and the spread of housing into rural areas and wildlands. This land-use change will be geographically uneven and disproportionately associated with the southern and western regions of the US (Panel 2), requiring large appropriations and redistributions of limiting resources such as water and nutrients. However, even in areas experiencing low population growth, the spatial expansion of urban and suburban land uses is much greater than the rate of population increase, due to a continuing pattern of declining developmental density and increasing land appropriation per capita (Theobald 2005).

> ***Hypothesis 2.*** *Human activities, their legacies, and the environmental template interact with gradients of air pollution and nitrogen (N) loading to produce substantial variation in ecosystem patterns and processes, from sub-continental to regional scales.*

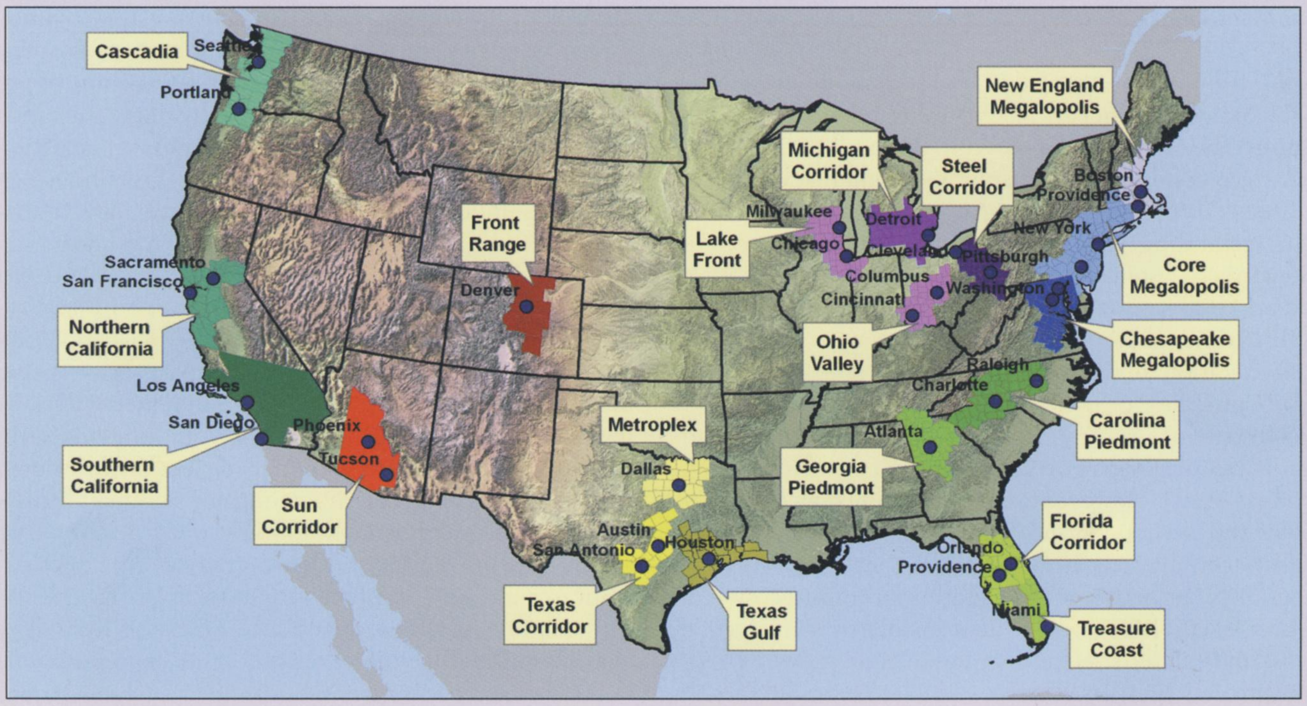
We expect pollution from urban and agricultural areas to influence ecosystem structure in profound ways. Emissions of nitrogen oxides, ozone, volatile organic compounds, other reactive gases, and aerosols derive from combustion sources (eg vehicles, power plants) in urbanized and urbanizing areas. Ammonia emissions are high in intensively fertilized agricultural and urban regions. Dust and aerosols are produced both from agricultural and urban construction activities, and as secondary products of reactive atmospheric chemistry. The impacts of these pollutants will occur both near emission sources and many hundreds to thousands of kilometers away, as a result of long-range transport and atmospheric chemistry. For example, excess ammonium and nitrate emissions from combustion and fertilization in the Midwest are implicated in chronically elevated reactive N-loading to sensitive ecosystems (such as high-elevation forests) in the Northeast and mid-Atlantic states (Driscoll *et al.* 2003; WebFigure 2). Nitrogen loading and ozone exposure cause changes in plant chemistry, photosynthesis, and ecosystem carbon balance in sensitive ecosystems (Aber *et al.* 1991). As transport and deposition of emissions continues, high N loading and air pollution (especially ozone exposure) may produce similar changes in less sensitive systems. Additional responses at these and larger scales may include shifts in dominant plant species (Arbaugh *et al.* 2003; Fenn *et al.* 2003; Stevens *et al.* 2004), export of nitrates and acidity to streams, rivers, and estuaries (Caraco and Cole 1999; Boyer *et al.* 2002; Donner *et al.* 2004), coastal eutrophication and

Panel 2. Megapolitan regions of the continental US

Seven megapolitan regions, each containing two or more megapolitan areas, have been identified for the continental US (Lang and Nelson 2007). In a megapolitan area, two or more large cities anchor the ends of a large corridor that is anticipated to fill with housing and other urban land uses over the early part of this century. This concept presents an exciting opportunity for ecologists, because regions differ markedly with respect to their social characteristics – history, current growth rate, density, and so forth (growth rate for 2000–2030 shown in the table below) – and can be superimposed on environmental gradients, such as that of climate (Marshall *et al.* [2008] in this issue) or topography (Figure 3).

Region	*Megapolitan area*	*Major cities*	*Growth rate*	*Color*
Megalopolis	New England	Boston/Providence	20	
	Core	NYC	20	
	Chesapeake	Baltimore/Washington	40	
Midwest	Steel Corridor	Cleveland/Pittsburgh	4	
	Ohio Valley	Cincinnati/Columbus	24	
	Michigan Corridor	Detroit	15	
	Lake Front	Chicago/Milwaukee	24	
Piedmont	Carolina Piedmont	Charlotte/Raleigh	45	
	Georgia Piedmont	Atlanta	55	
Florida	Florida Corridor	Tampa/Orlando	59	
	Treasure Coast	Miami	58	
Texas Triangle	Texas Gulf	Houston	51	
	Texas Corridor	San Antonio/Austin	62	
	Metroplex	Dallas/Oklahoma City	66	
Mountain West	Front Range	Denver	59	
	Sun Corridor	Phoenix/Tucson	81	
Pacific	Cascadia	Portland/Seattle	46	
	N California	San Francisco/Sacramento	43	
	S California	Los Angeles/San Diego	37	

Figure 3. *Megapolitan areas overlain on the topography of the continental US.*



harmful algal blooms (NRC 2000), and, possibly, increased invasiveness by N-demanding species (eg hybrid cattails, Eurasian *Phragmites* genotypes, winter annual grasses; Ehrenfeld 2003; Fenn *et al.* 2003).

Urbanization and pollution at regional and local scales

The megapolitan concept (Panel 2) provides an operational framework for predicting urbanization at the broadest scale. The phenomenon of urbanization is not restricted to the largest cities, however; although most people live in large cities (UNEP 2006), there are many more small cities than large ones. Diverse patterns of human settlement prevail across North America, from highly urbanized islands to sparsely populated forestland at high latitudes. Many gradients expressing these differences can be identified: cities from small to large, variable housing density, differences in the size of urban footprints (Folke *et al.* 1997; Luck *et al.* 2001), a shift from older cities to more suburban landscapes – all represent contexts that will affect the way that urbanization plays out. By studying contrasts or gradients between urban and wildland areas within regions and at local scales, scientists can develop a more comprehensive understanding of the ecosystem effects of urbanization and its feedbacks to society and management. The gradients we propose in this paper differ from the origi-

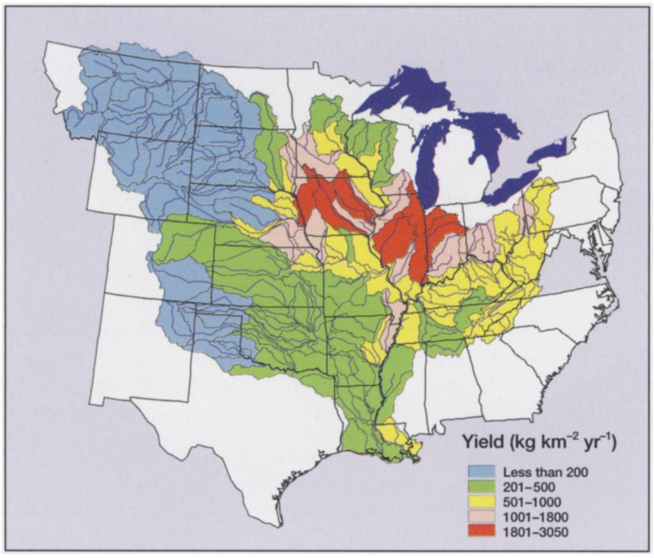


Figure 4. *Variation in N yield to the Mississippi River, illustrating the potential for specific regions to be "hotspots" of non-point-source pollution.*

nal urban–rural gradient paradigm described by McDonnell and Pickett (1990). A useful way to conceptualize the difference is to view the continental gradients as a collection of urban–rural gradients, each associated with individual metropolitan areas. Understanding the extent to which differences in human–ecosystem interactions along this collection of urban–rural gradients can be attributed to their contexts will advance urban ecology.

Generation and transport of pollutants at local to regional scales are well studied because of requirements for compliance with national air- and water-quality standards (see www.epa.gov/safewater/ and www.epa.gov/air/criteria.html). However, we do not know how the effects of air and water pollution from different human activities vary according to spatial context. For example, the concept of N saturation was developed for forest ecosystems (Aber *et al.* 1998) and is less frequently evaluated in grasslands, deserts, polar and alpine ecosystems, or lakes and streams (but see Wolfe *et al.* 2003; Bernot and Dodds 2005). The connectivity framework provides a useful context for understanding, within regions or even in local areas, how land change and pollution-generating activities affect nearby ecosystems. Hypotheses at this scale reflect connectivity both within and between urban areas, and with recipient ecosystems that are linked to them via wind or water vectors. We suggest three hypotheses that draw attention to differences and similarities across gradients in urban ecosystem structure and function and connectivity with the surrounding local–regional environment.

Hypothesis 3. *Within urbanizing regions, landscape alteration and management result in a relative homogenization of form and function of urban land cover across climate zones.*

Regardless of setting, urban ecosystems are strongly engineered by their inhabitants and may share similarities, despite great geographical or climatic differences (eg Walsh *et al.* 2005). For example, similar horticultural species are introduced in contrasting urban regions across North America. Redistribution of water and nutrients in urban landscapes may reduce differences between xeric and mesic regions, relative to the dramatic differences between corresponding wildland ecosystems. New conceptual models of social–ecological processes are needed to integrate causes and effects of development patterns and management choices on urban ecosystem function (see Panel 3).

Hypothesis 4. *Urbanization will generally increase connectivity via wind and animal vectors, but will disrupt connectivity via water vectors, especially at local to regional scales.*

Urbanization generates air pollutants that connect human settlements to adjoining wildland ecosystems. We therefore expect to see increased deposition of pollutants downwind and at potentially large distances from urban areas (Cooper *et al.* 2001). In addition, urban areas are a major source of the greenhouse-gas emissions underlying global changes in climate (Pataki *et al.* 2006). Wind transport of nitrogen, dust, and ozone from cities to outlying areas will alter plant productivity, ecosystem nutrient retention, and plant and microbial communities (Fenn *et al.* 1999). People also move both plants and animals. Comparison of species invasions and extinctions among land uses will show increased connectivity associated with human settlement for some species, although cities can also affect migration patterns by fragmenting habitat. Finally, because humans drastically modify water delivery and supply systems (eg streams, groundwater), connectivity via water will be disrupted, with dramatic consequences for aquatic ecosystems (see Panel 3). Some hydrologic connections will be increased as a result of urbanization (eg transport of water from source areas to cities, dispersal of invasive species along water corridors, sheet flow on impervious surfaces), while other hydrologic connections will be reduced (eg instead of long, slow flow paths from uplands to streams via groundwater, urban stormwater infrastructure creates new, short, fast flow paths that decrease ecological coupling between terrestrial and aquatic components of the landscape; Grimm *et al.* 2004).

Hypothesis 5. *Humans fundamentally change biogeochemical inputs, processing, flow paths, and exports in areas undergoing development.*

Research on urban ecosystems has expanded over the past decade and has seen some synthesis (Grimm *et al.* 2000; Pickett *et al.* 2001; Alberti *et al.* 2003; Grimm *et al.* 2008), yet

Panel 3. Urbanization in a water-limited region

In Phoenix, Arizona, the site of the Central Arizona–Phoenix LTER program, urbanization has produced wholly new environments with different thermal and hydrologic characteristics than the ecosystems they replaced (Figure 5). Understanding ecological consequences of these changes relies on an understanding of their impacts on social systems and, indeed, the reciprocal interactions that characterize an urban socioecological system. For example, the urban heat island in Phoenix presents a challenge both to trees (which show reduced growth in response to high temperature) and people (who increase their water use to cope with high temperature). But there are further interactions between heat, water, plants, and people that provide excellent examples of the need for integration. An unequal distribution of high summer temperatures disproportionately affects the poor and non-white residents, whose neighborhoods also have lower plant diversity. Detecting this pattern requires access to remote-sensing methods from the geosciences and social distribution data from the social sciences, as well as eco-physiological studies of thermal responses of trees and spatially referenced measurement of plant diversity. In terms of water systems, major hydrologic modification and redistribution of water resulting from over 100 years of human decisions have greatly enhanced plant productivity throughout the urban area at the expense of a major pre-settlement river–riparian ecosystem. Since 1938, the region's major river has not supported streamflow, except during floods. Recent riparian restoration projects along the Salt River have involved school children in low-income South Phoenix, who have created signage and built owl boxes, to name a few activities. One outcome of this educational program has been the transfer of knowledge about rivers and riparian ecosystems throughout families and communities.

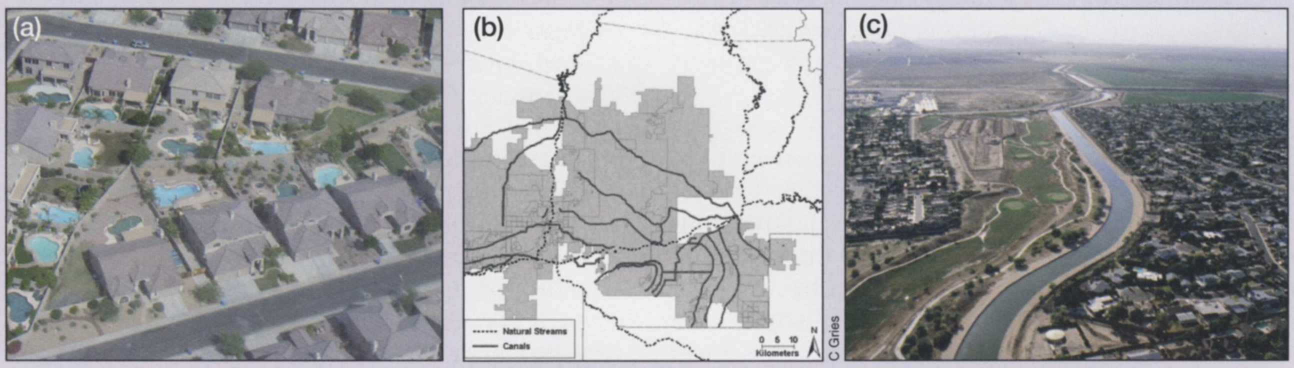


Figure 5. *Extensive modification of hydrologic systems, motivated by human desires for flood protection and water delivery, have replaced the historical broad river floodplain with a distributary canal system. Aquatic ecosystems no longer function like the streams they replace. (a) Swimming pools are a common feature of the hot, desert city of Phoenix. The urban heat island has worsened summer heat. For more information, see http://caplter.asu.edu. (b) The modern canal system and (c) a canal with riparian retention basin.*

this body of research consists largely of a collection of case studies. A continental network of urban sites would reveal how the major biogeochemical cycles are being altered by human activities (eg Kaye *et al.* 2006). We expect new, scaled models of biogeochemistry to emerge from observations of suburban, urban fringe, and exurban terrestrial and aquatic ecosystems. The fact that we have insufficient data on too few cities has precluded comparison of patterns of resource imports and their transformations within cities, which would allow us to test this hypothesis. At expanding urban fringes, we expect to observe changes in hydrologic balance and nutrient export as urban residents modify matter and energy fluxes through fuel, water, and fertilizer use, and as build-out increases impervious surface cover and modifies flow paths. Mercury, volatile organic compounds, endocrine disruptors, antibiotics, and nitrogenous pollutants released into streams from wastewater treatment plants or storm drainage will change species composition, nutrient retention capacity, and productivity of aquatic ecosystems. These processes have not been comprehensively evaluated across cities.

■ Cross-scale interactions

The influence of human land use and management on connectivity and ecosystems varies with spatial scale and region. Gradients in atmospheric deposition of N and sulfur at continental scales (eg WebFigure 2) result from prevailing air-transport patterns between source regions (eg industrial corridors, transportation hubs, agricultural regions) and sink regions (eg rural regions, wildlands, natural areas). Coastal and freshwater eutrophication can be traced to upland agricultural activities (particularly N and P fertilizer use; Figure 4) in the Midwest and Gulf of Mexico, and to urbanization and atmospheric deposition in the Northeast (NRC 2000; Driscoll *et al.* 2003). Urban thermal regimes vary compared to their surroundings, owing to the increased heat capacity of the infrastructure coupled with altered evapotranspiration, which is reduced in eastern cities relative to natural ecosystems, and enhanced in irrigated, semi-arid cities. However, the cross-scale interactions of urban heat islands with regional and global climate change are unknown. Sharp regional gradients in atmospheric and aquatic pollutants originating at urban point sources are superimposed on broader continental gradients of climate and long-range atmospheric or riverine transport of materials.

Perhaps most importantly, the scales at which human decision-making and actions occur are often inconsistent with the scales at which ecosystems are changing (Cumming *et al.* 2006). This mismatch in scale may be true both for causative action (eg automobile use by individuals and global atmospheric forcing of increased CO_2) and corrective action (eg amelioration of eutrophication by point-source wastewater treatment). We offer the following hypothesis.

> ***Hypothesis 6.*** *(a) Urbanizing regions will be less vulnerable than wildland ecosystems to many broad-scale, directional changes in climate due to the capacity of humans to modify their environment, and cities' access to political power and resources. However, (b) urbanizing regions will be more vulnerable than rural and wildland ecosystems to extreme events, because of the greater concentration of people and infrastructure that cannot be moved or modified over the short term. In addition, (c) efforts by urbanizing regions to adjust to change will place added stress on rural and wildland ecosystems that are connected to cities due to greater resource exploitation.*

Because the vast majority of the North American population lives in urban areas, the impacts of climate change on cities are of great interest. Urban areas and their institutions are able to adjust to directional and even some relatively abrupt changes, for example by increasing water supply during droughts or by strengthening infrastructure in response to the threat of hurricanes or sea-level rise. In addition, urbanization has a profound effect on local climatic conditions. Large urban areas essentially create their own climate: lighter winds, less humidity, more or fewer rainstorms compared to surrounding rural areas. Moreover, urban engineering, conservation, and landscaping alternatives allow urban residents to limit the variability of the climate that they experience (McPherson and Biedenbender 1991; Taha *et al.* 1999; Akbari 2002; Akbari and Konopacki 2005; Harlan *et al.* 2006; Stabler *et al.* 2006). In wildland ecosystems, climate mitigation options are more limited. We expect that human actions will, in general, degrade ecosystem services of linked wildlands (relative to those outside the influence of the urbanizing region), by resource extraction and air and water pollution.

■ Testing hypotheses at continental, regional, and local scales

Understanding how ecosystems respond to urbanization and pollution drivers requires accurate long-term tracking of land-use and land-cover change. In order to assess and interpret the dynamics of land change across scales, "wall-to-wall" (ie spatially continuous) continental coverage is necessary. Sub-continental and regional analyses would benefit from focused digital retrieval and analysis of more detailed data sources; such sources are not completely available today. At all scales, acquiring and analyzing historical records, human demographic data, resource consumption and transformation statistics, and imagery is requisite to testing hypotheses (eg Hypothesis 1) regarding drivers of land change in all regions of the continent. These data sources are used locally by individual investigators, but are not yet synthesized over larger areas. Historical resources are of particular value, as many current dynamics and future responses are conditioned by ecological legacies (eg soil, vegetation, biotic patterns and processes) resulting from past human or natural changes (Foster *et al.* 2003; Lewis *et al.* 2006). The tools needed for geographical analysis of land-cover changes and ecological responses will be essential for testing the hypotheses presented above.

Testing hypotheses at multiple scales will require a concerted and coordinated monitoring effort (ie direct observation of land change and accompanying ecosystem responses). Changes in atmospheric and hydrologic connectivity caused by urbanization (Hypothesis 4) might be assessed using atmospheric tracers that are incorporated into biota (eg Zschau *et al.* 2003; Hsueh *et al.* 2007) or by comparing stream discharge patterns before and after urbanization (eg Rose and Peters 2001). Measurements of ecosystem responses to urbanization and pollution at sites distributed continentally across various gradients would address Questions 1–3 (Panel 1) and, most specifically, test Hypothesis 4. At each site, scientists should measure the changes that ensue as an urban fringe area experiences increased housing and transportation system development, including those related to pollution. Intensive work within megapolitan regions would enable comparisons across major urbanizing regions of the continental US, addressing Questions 1–3 (Panel 1) and Hypotheses 2 and 4–6. These are complementary rather than competing approaches, which will ensure a more complete understanding of the urbanization phenomenon when applied simultaneously.

To answer Question 4 (Panel 1), sensors capable of measuring atmospheric and aquatic pollution should be established at a national network of wildland sites, such as an expansion of the current NADP sites to include greater spatial coverage (http://nadp.sws.uiuc.edu). Drought effects on dust emissions are expected to be greatest over the mid-latitude continental interior (IPCC 2001), and will combine with land-cover change throughout the continental US to increase fugitive dust emissions from suburban and urban locations. Because dust is often carried long distances (up to thousands of km) from its point of origin, the impacts of urbanization-induced dust emission should be observed across the continent.

A research infrastructure is needed to enhance our ability to track changes in emissions, transport, and deposition of N and other pollutants as they relate to changes in land use and human activities, and to assess the effects of these processes on ecosystem structure, function, and services. Such an infrastructure may be provided to some extent by existing networks and research programs, such as the Long Term Ecological Research Network (www.lternet.edu) and the National Atmospheric Deposition Program, in combination with networks coming on line, such as the planned National Ecological Observatory Network.

Networking observations, conducting syntheses, and forecasting

An important goal is predictive understanding of how human settlement patterns will alter ecosystem services and resource utilization at the continental scale. This predictive capacity is essential for a wide range of social, economic, and environmental national policy making, and for management efforts at local to national levels. A new generation of simulation models – spatially explicit socioeconomic and demographic models of human settlement, consumption, and land management dynamics that are integrated with hydrological–biogeochemical–land-use–invasion models – is needed to address these new questions across scales. Advances in cyberinfrastructure will be required to allow real-time input to be provided to these new, coupled models. Furthermore, a large-scale, networked research program has the potential to catalyze a move from empirical modeling, based on statistical extrapolation of historical trends, toward a forecasting foundation based on general principles governing land change. This theory development will arise from an iterative cycle of forecasting, observation, and change detection, refinement of theory and guiding principles, and repeated forecasting. Feedbacks from science to society should result in major changes in long-term forecasts as we witness human system responses to the recognition of its own impacts on the environment.

Conclusions

Urbanization is a globally important land-use change that is closely associated with climate change and pollution. Yet knowledge of ecosystem responses to urbanization and of the urban socioecosystems themselves is based, at present, on individual and often idiosyncratic case studies. Spatially contiguous observation of land-cover change coupled with a continental-scale network of observations of ecosystem responses, supplemented with historical and demographic data, will enable a transformation in our understanding of these complex, interactive processes and how they may be expected to change under future climate and human population scenarios. New, coupled ecosystem models and forecasting will play a key role in this transformation of the science.

In addition to the clear benefit to scientific knowledge, providing timely information on land change, urbanization, and pollution has the potential to enhance decision making on many levels. In turn, urbanization, pollution, and human influences on land change represent highly visible and comprehensible elements of human interactions with their environment. Establishing urban and urban-fringe sites for scientific investigation will thus offer unparalleled opportunities for outreach and educational activities.

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