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Maintaining ecological integrity and sustaining ecosystem function in urban areas

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Urbanizing regions increasing challenge the ecosystem's capacity to deliver important ecological services to the human population and support human well-being. Scholars of urban ecology have hypothesized that the patterns of urbanization control ecosystem dynamics through complex interactions and feedback mechanisms linking urban activities and their spatial organization to land cover and environmental change. However, empirical studies of the underlying processes and mechanisms linking urbanization patterns and ecosystem dynamics are still extremely limited. In this paper, I present a framework linking urban patterns to ecosystem functions and discuss a set of hypotheses based on the empirical evidence established in the literature.

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Urbanizing regions pose increasing challenges to ecosystems' health and functioning. Urbanization affects the structure and function of Earth's ecosystems through the transformation of the natural landscape, alteration of biophysical processes and habitat, and modification of major biogeochemical cycles [1•,2•,3•,4••]. These changes in turn affect the ecosystem's capacity to deliver important services to the human population and support human well-being. During the last three decades we have learned a great deal about the interactions between human activities and ecosystem function in urbanizing regions. However, empirical studies of the underlying processes and mechanisms linking urban patterns to ecosystem dynamics are still extremely limited.

While ecological conservation has traditionally targeted areas of high natural significance, the expected increase in urbanization and associated impacts demand that we expand its scope to include urbanizing regions. The role of urban areas in maintaining ecosystem function will become increasingly important to protect both local and global ecosystems. Urban areas occupy only about ~6 of the global land area but concentrate on the largest number of people and activities, and their physical structure may be a determining factor of the amount of resources urban dwellers use and of emissions they generate. Scholars of urban ecology have hypothesized that the patterns of urbanization control ecosystem dynamics through complex interactions and feedback mechanisms linking urban activities and their spatial organization to land cover and environmental change [5••,6•]. In this paper, I present a framework linking urban patterns to ecosystem functions and discuss a set of hypotheses based on the empirical evidence established in the literature.

Mechanisms linking patterns to functions

Earth's ecosystems are increasingly influenced by both the pace and patterns of urban growth, and to a great extent the future of ecosystems will depend upon how we will be able to make urban regions sustainable. All of the population growth expected in the next 20 years, (approximately two billion people) will be concentrated in urban areas. The world urban population will reach more than 60% (4.9 billion) by the year 2030. This is three times the total population of the planet 100 years ago (1.7 billion people) [7•]. The geographic distribution of the urban population will not be equal. The urban population of developing countries is projected to double, from just under two billion in 2000 to nearly four billion by 2030. A large proportion of the urban population lives in very poor conditions. According to the UN, more than 1 billion people lived in areas classified as slums in 2005 (UN 2007).

In urbanizing regions, both human factors (e.g. demography, economics, institutions and policies) and biophysical factors (e.g. topography and climate) drive human and biophysical patterns and processes. These in turn affect ecosystem function (both biotic integrity and human well-being) and can generate system shifts depending on the development pathways. Ecosystem function supports important services in urban areas. They provide clean water, sequester carbon and filter pollutants, moderate climate conditions, control flooding, protect soils from erosion, and maintain biodiversity. Changes

Table 1

Ecosystem patterns, processes, and functions: a synthesis of the established relationships, directions (↑↓), and uncertainties (?) between urban patterns and ecosystem functions through various ecosystem processes ([7•], Table 3.1, pp. 64–65).

Process	Pattern				
	Land cover	Land use	Transportation	Energy infrastructure	Water infrastructure
Climate	↑ Impervious surface ↑ Grassland ↓ Forest cover	↑ Heat ↑ CO_2 emissions	↑ Heat ↑ CO_2 emissions	↑ Heat ↑CO_2 emissions	
Hydrology	↑ Impervious surface ↑ Grassland ↓ Forest cover ↑ Dams	↑ Industrial water use ↑ Agricultural water use ↑ Residential water use	↑ Impervious surface ↑ Grassland ↓ Forest cover	↑ Dams	↑ Water extraction ↑ Hydrologic connectivity ↑ Water budget
Geomorphology	↓ Riparian area ↓ Wetlands ↑ Gravel extraction	↑ Riparian clearing ↓ Pervious surfaces and soil column	↑ Riparian clearing ↓ Pervious surfaces and soil column	↑ Dams	↑ Channel modification ↑ Channel incision or ‘‘down cutting’’
Biogeochemical	↑ Impervious surface ↓ Forest cover ↓ Vegetation	↑ Fertilizers ↑ Pesticides ↑ Herbicides ↑ Toxic emissions	↑ CO_2, NO_X, CO, SO_2, and VOCs emissions ↑ Road salting ↑ Oil leakages	↑ CO_2, NO_X, CO and SO emissions	↑ Septic and waste water treatment emissions ↑ Waste water overflow emissions
Biotic interactions	↓ Riparian area ↓ Wetlands ↓ Forest cover ↑ Forest fragmentation ↑ Invasives	↓ Riparian area ↓ Wetlands ↓ Forest cover ↑ Forest fragmentation ↑ Invasives	↓ Riparian area ↓ Wetlands ↓ Forest cover ↑ Forest fragmentation ↑ Invasives	↓ Riparian area ↓ Wetlands ↑ Forest fragmentation	↓ Riparian area ↓ Wetlands ↑ Forest fragmentation

Process	Function					
	Primary production	Hydrologic function	Nutrient cycling	Biodiversity	Habitat provision	Disturbance regulation
Climate	? Photosynt. ?Plant growth	↑ Temp. ↓ Snow pack ↑ Runoff	↑ Nutrient losses	↓ Species div ↑ Invasives ↑ Geographic shifts in ranges ↑ Shifts in the timing of breeding	↑ Temp.	? Weather events/variability ↑ Invasives ↑ Fire/drought, insect/path. outbreaks ↑ Landslides
Hydrology	? Water availability	↑ Runoff ? Base Flow ↑ Nutrients ↑ Toxics ↑ Flashiness	↓ N retention	↓ Fish pop. ↓ Macroinvertebrates diversity ↑ Tolerant/generalist species	↓ Water qnty. ↓ Substrate ↓ Habitat div. ↑ Temp. ↓ Woody deb.	↑ Flooding ↑ Drought ↑ Erosion ↑ Sedimentation
Geomorphology	? Nutrient availability	↑ Runoff ? Base Flow ↑ Temp. ↑ Sediment ↑ Nutrients	↓ Organic matter ↓ Nutrient uptake	↓ Fish pop. ↓ Macroinvertebrates diversity ↑ Tolerant/generalist species	↑ Channel width ↑ Pool depth ↓ Channel complexity ↓ Spawning, rearing and hiding sites	↑ Flooding ↑ Erosion ↑ Sedimentation ↑ Landslides

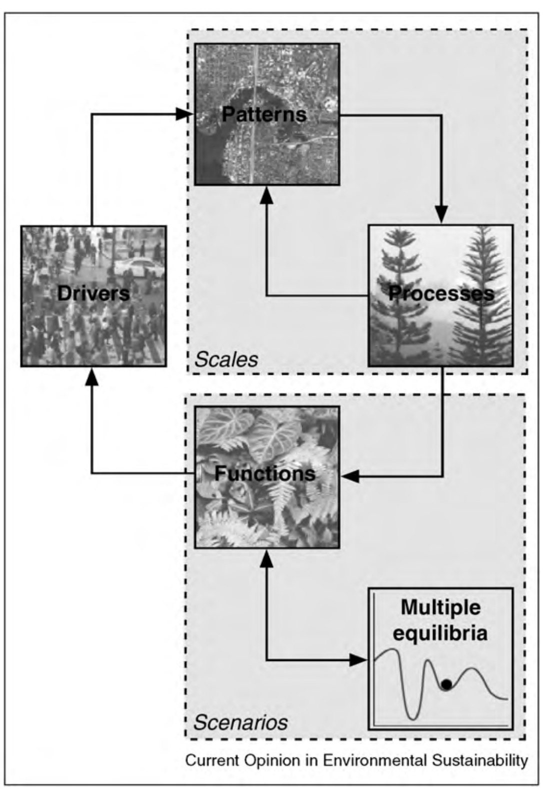
Table 1 (*Continued*)

Process	Function					
	Primary production	Hydrologic function	Nutrient cycling	Biodiversity	Habitat provision	Disturbance regulation
Biogeochemical	? Nutrient availability	↑ Temp.	↑ Soil NO_3 and nitrification	↓ Species div.	↓ Habitat diversity	↑ Nutrients
		↑ Sediment		↑ Algae		
		↑ Nutrients	↓ Soil Denit.	↑ Tolerant/generalist species	? Food sources	
		↑ Toxics, DO, pH, PAHs, PCBs, Chloride, Organics	↑ Eutroph.			
			↓ Organic debris			
			↑ N sources			
Biotic interactions	↑ Seed production	? Water use efficiency	↑ Organic material	↓ Species div.	↑ Competition	↑ Invasives
	? Carbon use efficiency		↑ Eutroph.	↓ Native species		↑ Insect/pathogen outbreaks
			? Trophic interactions	↑ Synanthropic species	? Nest predation	
			? Ecosystem metabolism			

in ecosystem functions feed back into drivers of change (Figure 1, [3•]).

Urbanized areas have extraordinarily large ecological ''footprints'' with the largest proportion of resource uses (e.g., residential water and energy use) and carbon emissions [39]. Urbanization affects primary productivity, nutrient cycling, hydrological function, and ecosystem dynamics through direct and subtle changes in climatic, hydrologic, geomorphic, and biogeochemical processes and biotic interactions [7•]. By explicitly linking urban patterns and processes to ecosystem functions, it is possible to articulate testable hypotheses regarding how urbanization affects ecosystem function and synthesize findings from existing studies (Table 1, [7•]). Several authors have provided various initial syntheses of what we know of the ecology of cities [2•,8] and the urban ecology literature is rapidly expanding. These syntheses reveal the gap in the study of urbanization patterns and the uncertainty associated with specific mechanisms and interactions.

Figure 1



Conceptual model of coupled human-natural systems [3•] (*modified* in Alberti and Hutyra [33]).

Urbanization is a major driver of land conversion. Land development and human activities in urbanizing regions alter land cover and the availability of nutrients and water, affecting population, community, and ecosystem dynamics. Urbanized areas imply an increase in impervious land area which affects both geomorphological and hydrological processes, thus causing changes in water and sediment fluxes [9,10,36,47]. Compared with drainage basins of forested areas, urban basins with 10–20% total impervious surface may double surface runoff and significantly shorten the lag times between precipitation input and discharge. They also generate higher flood peak discharges during storms [11]. Furthermore, due to stream incision patterns, water tables tend to be lower in urbanized sites [40]. Impervious surface and the generation of heat from various combustion processes in urban areas modify the microclimate and air quality. The urban heat island effect, which in turn serves as a trap for atmospheric pollutants, is the best-known example of inadvertent climate modification [44,52].

But the amount of land conversion imposed by urbanization is only part of the equation linking urbanization to ecosystem function. Most importantly, land conversion takes place on the most productive lands [45] or vulnerable lands [49]. Using the night light footprints derived from DMSP/OLS satellite images of a digital soils map, Imhoff et al. [45] indicate that most of urbanization is taking place on the best soils — with the fewest limiting factors. According to Imhoff et al. [12•] change in NPP due to urbanization in the US is 0.04 Pg C, or 1.6% of its pre-urban NPP value. But the effects of urbanization vary across biomes and world regions. Imhoff et al. [12•] show that urbanization can increase NPP in resource-limited regions by bringing water to arid areas and ''urban heat islands,'' but the benefits do not offset the overall negative impact of urbanization on NPP [12•]. Furthermore, an analysis of the percentage of urban and rural population across world's regions found no evidence of urban populations concentrated in areas suitable for cultivation [35].

Urbanization also affects biogeochemical processes by adding nutrients and modifying the mechanisms that control the spatial and temporal variability of nutrient sources and sinks [13•,14,4••,41,53]. Emerging studies in Baltimore, Phoenix and Seattle are now showing that complex relationships generate unique biogeochemical effects. Despite the variability of local biophysical settings and socio-economic activities within cities, for example, the coupling of human and natural processes may be creating a distinct biogeochemistry. Several studies provide evidence on the effect of urbanization nutrient export and retention [15,38,42,46,50]. Sources of nutrients (both point and non-point) in urban areas contribute to N and P loads to urban river reaches [51]. The built landscape pattern and urban infrastructure also modify the ways that nutrients are transported across the landscape. In cities, the built infrastructure and artificial drainage systems also affect nutrient cycles when nutrients are released from municipal wastewater and from combined sewer-stormwater overflow systems in urban surface waters. Roads, parking lots, ditches, gutters, stormwater drains, detention basins, and lawns accumulate large amounts of nutrients. When that happens they can become hot spots for denitrification [11,38].

Urban development affects the carbon cycle through both vegetation clearing and fossil fuel emissions influencing both carbon stocks and fluxes [16•]. Developed land impacts carbon sequestration by clearing vegetation but the ability of cities to maintain such function remains highly uncertain [17••]. Estimates attribute 40% of total fossil fuel emissions in the United States to the transportation and residential sectors (WRI, 2005). The number and size of households affect the number and size of housing units with consequences for the amount of land cleared and energy uses. But the pattern of urban development may be key in determining the magnitude of urban carbon impacts. The spatial distribution of residential and commercial housing units affects both the extent of canopy cover loss and commuting patterns of urban residents [34,37,48].

Change in land cover and land use associated with urbanization affects natural habitat and biodiversity through productivity, disturbance, and subsidies. Both the loss and fragmentation of natural cover due to urbanization have direct and indirect impacts on the diversity, structure, and distribution of vegetation with important consequences for the distribution, movement, and persistence of species. Biodiversity plays a key role in maintaining ecosystem functions and urbanization is associated with several changes in biotic interactions and tropic dynamics that affect the viability and distribution of species [18,19]. The study of urban impacts on ecosystem function associated with loss of biodiversity is expanding from a traditional focus on the number of species to the complex mechanisms that links human activities and settlement patterns to selective phenotype trait diversity [20•]. Also changes in disturbance regimes generated by urbanization can have an influence on the relationship between biodiversity and ecosystem function [21•]. High concentrations of human populations and activities modify the magnitude, frequency, and intensity of natural disturbances (i.e. erosion, flooding, fire, etc.) and also cause unprecedented human disturbances in ecosystems (i.e. biogeographic barriers created by roads, canals, and park boundaries) [22,23]. Human activities introduce novel disturbances, chronic stresses, unnatural shapes, and/or new degrees of connectedness. Land use, in addition, may introduce homogeneous patterns causing suppression of the natural processes that maintain diversity.

Consumption versus urban structure

Increasing consumption levels associated with countries' economic development partially explain the ecological impact of urbanization. Even though as countries develop they increase their resource efficiency and reduce their environmental impact per unit of production, overall per capita environmental impact in the developed world is several orders of magnitude higher than that of developing countries due to greater consumption. For example, per capita emissions in developed regions are typically as much as ten times those of developing countries [43]. Income differentials across cities also explain the per capita land area [24•], although the exact difference in magnitude depends on the definition of urban land assumed in these estimations [25].

Greater uncertainty surrounds the role that the city's physical structure plays as a determinant of the impact of urban dwellers on ecosystems. After controlling for income, several authors have proposed that urban form (e.g., population density or degree of concentration) explains the level of resource consumption and emissions associated with urbanization. For example, in a study of world cities, Kenworthy and Laube [26] attribute per capita gasoline consumption and related CO_2 emissions to differences in cities' density. However comparing urban density across cities is a challenging task. Furthermore, the mechanisms underlying the relationships between urban form and ecological impacts are still not fully specified and tested [32].

Scholars of ecology have initially hypothesized that impacts on ecosystem processes change predictably with distance from urban centers [27]. Empirical studies have challenged these initial assumptions. McDonnell and Pickett [28] study of the urban to rural gradient in New York revealed a pattern that was the opposite of what was expected. Urban forests exhibit faster litter decomposition and nitrification rates than the rural forests. These impacts were ameliorated in the urban environment. Both the heat island effect and the introduction and colonization of (non-native) earthworms in the urban forests were hypothesized to drive these results.

But how do alternative urban development patterns influence ecological systems along this gradient? Most studies of the impacts of urbanization on ecological systems correlate changes in these systems with simple aggregated measures of urbanization (e.g., human population density, percent impervious surface). We do not know the effects of different urban forms, densities, land use mix, and alternative infrastructures. We do not know, for example, how clustered versus dispersed and monocentric versus polycentric urban structures differently affect ecological conditions. Nor do we understand the ecological tradeoffs associated with different housing or alternative infrastructures.

To fully integrate human and ecosystem dynamics, urban ecological scholars should integrate mass-balance studies with empirical studies of ecosystem responses on urban–rural gradients [27,13•,4••]. We also need to expand our observations and measurements to assess differential effects associated with alternative patterns of urbanization. We do not fully understand the effect of spatial heterogeneity on mechanisms that regulate nutrient export and retention much less in urbanizing landscapes. It is critical that we explore the multiple interactions between simultaneous stresses and disturbances across an urban-to-rural gradient so we can develop predictions of future urban biogeochemistry. One unresolved question concerns how the urban infrastructure mediates the biogeochemistry of an urbanizing region.

The question of how patterns of human settlements affect ecosystem functioning is becoming increasingly important in ecology [1•,2•,29•]. While both ecological and socio-economic studies have attempted to establish relationships between patterns and processes in urban landscapes, they have done so in their respective domains. Only recently, various disciplinary approaches have been combined to study the interactions between complex human behaviors and ecosystem function in urban ecosystems and expand the concept of ecosystem function to include human and ecological components. When studying the interactions between humans and ecological processes in urban ecosystems, we need to consider the many socioeconomic and biophysical factors that work simultaneously at various levels and provide important feedback mechanisms. These complex interactions give rise to emergent phenomena whose properties cannot be understood by studying in isolation the properties of socioeconomic or ecological systems.

A research agenda

Understanding the relationships between development patterns and ecosystem function can help generate a theory of interactions and feedback mechanisms between human decisions and ecological resilience in urbanizing ecosystems [30••]. In the book *Advances in Urban Ecology* (2007), I have suggested that linking urban patterns to ecosystem function is critical to advance urban ecological research and develop strategies to minimize the impacts of urban development. Strategic decisions on issues such as the planning of urban growth and investment in public infrastructure require synthesis of extraordinarily complex and rapidly evolving knowledge from a broad range of disciplines (e.g., natural resource management, fisheries, business, urban planning, civil engineering, political science, public health, law, and economics). It is clear from emerging studies that the interactions between urban patterns and ecosystem function are controlled by multiple agents and mechanisms operating at a variety of temporal and spatial scales. We can also investigate how land-use intensity and urban patterns interact to affect ecological conditions. For example, we can investigate how a modification of the landscape structure at a subwatershed scale interacts with local effects of the land use on the riparian zone. Moreover, we can establish what roles the urban infrastructure play in the overall impact.

Advancing the study of coupled human-natural systems in urbanizing regions is critical to develop future scenarios. We do not know how interactions between urbanization patterns and ecosystem function may change under alternative futures. We need to move beyond idiosyncratic studies towards integrated, cross-regional comparisons [31•]. Urban ecology requires comparative framework and common metrics for identifying and testing hypotheses of how urbanization patterns affect mechanisms governing urban ecosystem dynamics. There is a great deal of systematic observations that need to be accomplished before we can fully understand how to build resilient urban systems. But building on exiting knowledge we can start to change planning practice. Even as we start to learn from observations about what that makes a resilient urban region, rapid change will inevitably create increasing uncertainty and surprise over the long term.

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