Urban Systems

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Introduction

Urbanization is a global multidimensional process that manifests itself through rapidly changing human population densities and changing land cover. The growth of cities is due to a combination of four forces: natural growth, rural to urban migration, massive migration due to extreme events, and redefinitions of administrative boundaries. Half of the world's population today lives in urban areas, a proportion expected to increase by 2/3 within 50 years. Today, over 300 cities have a population of more than 10^6 and 19 megacities exceed 10^7. As urbanization is accelerating, the growth of cities forms large urban landscapes, particularly in developing countries. (Urban landscape is here defined as an area with human agglomerations with $>50\%$ of the surface built, surrounded by other areas with 30–50% built, and overall a population density of >10 ind. ha^{-1}.) For example, during the last 20 years in China, clusters of cities have emerged forming at least five mega-urban landscapes. These large and densely urbanized regions have each between 9 and 43 large cities located in close proximity and a population ranging from 27 to 75 million people. This rapid urbanization represents both a challenge and an opportunity to ensure basic human welfare and a viable global environment. The opportunity lies in that urban landscapes also are the very places where knowledge, innovations, human and financial resources for finding solutions to global environmental problems are likely to be found.

Since urbanization is a process operating at multiple scales, factors influencing environmental change in urban landscapes often originate far beyond city, regional, or even national boundaries. Fluctuation in global trade, civil unrest in other countries, health pandemics, natural disasters, and possibly climate change and political decisions are all factors driving social–ecological transformations of the urban landscape.

Mismatches between spatial and temporal scales of ecological process on the one hand, and social scales of monitoring and decision making on the other have not only limited our understanding of ecological processes in urban landscapes, they have also limited the integration of urban ecological knowledge into urban planning. In ecology there is now a growing understanding that human processes and cultures are fundamental for sustainable management of ecosystems, and in urban planning it is becoming more and more evident that urban management needs to operate at an ecosystem scale rather than within the traditional boundaries of the city.

Although studies of ecological patterns and processes in urban areas have shown a rapid increase during the last decade, there are still significant research gaps that constrain our general understanding of the effects of urbanization processes. The vast majority of studies so far have been short term (one to two seasons), conducted in cities in Northern Europe or the US, have lacked experimental approaches, focused on either birds or plants, while other taxa are rarely represented and have only included portions of a rural–urban gradient. Most significantly, we nearly completely lack studies in rapidly growing urban landscapes in tropical developing countries that are rich in biodiversity and are just beginning to address the complexity of human settlements in the tropics.

Of further significance is that urban landscapes provide important large-scale probing experiments of the effects of global change on ecosystems, since, for example, significant warming and increased nitrogen deposition already are prevalent and because they provide extreme, visible, and measurable examples of human domination of ecosystem processes. Urban landscapes may be viewed as numerous large-scale experiments producing novel types of plant and animal communities and novel types of interactions among species, and as such deserve the full attention of not only evolutionary biologists and ecologists but also of students of social–ecological interactions.

Urbanization and Plant and Animal Communities

Urbanization is today viewed to endanger more species and to be more geographically ubiquitous than any other human activity (Fig. 1). For example, urban sprawl is rapidly transforming critical habitats of global biodiversity value, for example, in the Atlantic Forest Region of Brazil, the Cape of South Africa, and coastal Central America. Urbanization is also viewed as a driving force for increased homogenization of fauna and flora. In the urban core in Northern Hemisphere cities, a similar set of species is recorded that is, often cosmopolitan plant and animal species tolerant of anthropogenic impacts. For example, the composition of communities of wildlife species found in cities across the US is remarkably similar despite large variation in climate and geographical features. A common pattern among cities is that they often show a high turnover of species with losses of native species and gains of non-natives over time. For example, it is documented that New York has lost 578 native plant species while it gained 411, and Adelaide lost 89 while it gained 613 new plant species over a period of 166 years. Although cities may be species rich,

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Fig. 1 Cape Town, South Africa with more than 3 million residents is located in the Cape Floristic Region, an area with the highest density of plant species in the world with more than 9600 plants species of which 70% are endemic. Through initiatives like Working for Wetlands and Cape Flats Nature, successful efforts are taken to address the large challenge of conserving precious biodiversity in fragmented natural habitats in an urban setting where poverty is widespread. These initiatives focus on building bridges between people and nature and demonstrating benefits from conservation for the surrounding communities, particularly areas where incomes are low and living conditions are poor, and encouraging local leadership for conservation action.

frequently having higher species diversity than surrounding natural habitats, this is often due to a high influx of non-native species and formation of new communities of plants and animals. A trend of increasing non-native species from the suburbs to the urban core is well documented for plants, birds, mammals, and insects. For example, in Berlin the proportion of novel species increased from 28% in the outer suburbs to 50% in the built-up center of the city. In New York, the abundance and biomass of earthworms increased tenfold when comparing rural and urban forests, mainly due to increased numbers of introduced species in urban areas. Over broad geographical scales urbanization seems to have an effect of convergence in species composition with loss of native species and invasion of exotics. Nevertheless, a remarkable amount of native species diversity is known to exist in and around large cities, such as Singapore, Rio de Janeiro, Calcutta, New Dehli, and Stockholm.

Interestingly, the number of plant species in urban areas often correlates with the human population size. Species number often increases with log number of human inhabitants, and that relationship is stronger than the correlation with city area. The age of the city also affects species richness; large, older cities have more plant species than large, younger cities. Also of interest is that diversity may correlate with measures of economic wealth. For example, in Phoenix, USA, measures of plant and avian diversity in urban neighborhoods and parks show a significant positive correlation with measures of median family income levels.

In general, urban landscapes present novel ecological conditions, such as rapid rate of change, chronic disturbances, and complex interactions between patterns and processes. Organisms that have survived in urbanized areas have been able to do so for at least two reasons: (1) they evolved rapidly and adjusted genetically or (2) they were largely preadapted to this environment and required little or no genetic adjustment. There are several documented cases of rapid evolution in urban areas, involving, for example, tolerance to toxic substances and heavy metals in plants, such as lead tolerance in urban roadside *Plantago lanceolata*. Among insects there are many cases of rapid evolution in urban areas, notable example being the famous case of industrial melanism among Lepidoptera in UK, a phenomenon also documented from areas in USA, Canada, and elsewhere in Europe. Also of interest is that specific urban and rural races have been identified within well-studied *Drosophila* species.

In **Table 1** we have summarized some of the effects of urbanization including abiotic and biotic changes. Human activities may cause increased deposition of nutrients such as nitrogen and phosphorus and emission of toxic chemicals which influence urban soil processes. Decomposition rates in urban soils are often negatively affected by pollution and toxic chemicals, but positively affected by increased soil temperature. Decomposition rates may therefore often be higher in urban than in rural soils. However, urban litter tends to have higher C:N ratios and therefore also tends to be more recalcitrant than rural litter. Urbanization affects in complex ways both directly and indirectly C-pools and N-transformation rates and contrasting dynamics in urban and rural soils is an area where much more research is needed.

Biotic changes influencing ecosystem functioning are listed in **Table 1**. There are a number of reasons why new human-imposed scales for ecological processes are found within urban areas. First, compared with ecosystems in rural areas, urban systems are highly patchy and the spatial patch structure is characterized by a high point-to-point variation and degree of isolation between patches. Second, disturbances such as fire and flooding are suppressed in urban areas, and human-induced disturbances are more prevalent as well as intense human management of urban habitats. Third, because of the `heat-island' effect, that is, higher mean temperatures in cities than in the surroundings, cities in temperate climates have significantly longer vegetation growth periods. Fourth, ecological successions are altered, suppressed, or truncated in urban green areas, and the diversity and structure of communities of plants and animals may show fundamental differences from those of nonurban areas. In general, with increasing urbanization there is a trend toward dominance of generalist species with high reproductive capacity and short generation times.

Table 1 Ecological effects of urbanization

Physical and chemical environment	*Population and community characteristics*	*Ecosystem structure and function*
Air pollution increases	Altered reproductive rates	Altered disturbance regimes
Hydrological changes	Genetic drift, changes in selection	Altered succession
Local climate change	Social and behavioral changes	Altered decomposition rates
Soil changes	High species turn over, increase of exotic species	Altered nutrient retention
Water changes	Loss of K-species and gain of r-species	Habitat fragmentation
	Increased dominance of generalist species	Changes in trophic structure, domination of omnivores

Modified from McDonnell, M.J., Pickett, S.T.A., 1990. Ecosystem structure and function along urban–rural gradients: An unexploited opportunity for ecology. Ecology 71, 1232–1237.

Urban Habitats and Gradient Analyses

Urban habitats are extremely diverse and examples include parks, cemeteries, vacant lots, streams and lakes, gardens and yards, campus areas, golf courses, bridges, air ports, and landfills. These habitats are highly dynamic, influenced by both biophysical and ecological drivers on the one hand and social and economic drivers on the other. Urban landscapes often represent cases of extreme habitat fragmentation. Habitat patches in the urban core are more or less strongly isolated from each other by a matrix of built environment making dispersal risky and difficult at least for poorly dispersing organisms. There are numerous studies analyzing effects of isolation of urban habitats and, for example, in urban gardens in UK, the best predictor of species richness of ground arthropods was found to be the proportion of green areas within a 1 km radius of the sampling site. Analyses of the distribution of plant species in vegetation fragments in Birmingham, UK showed a positive correlation between the density of patches available to a species and the proportion of these patches that was occupied. For many plant species the rate of occupancy increased with site age, area, and similarity of adjacent habitats. Similarly, for urban amphibian assemblages in Melbourne, Australia, an increase in species richness was associated with pond size and a decrease with increasing isolation. Habitat quality also influenced species composition. The importance of isolation is likely to increase over time and, for example, in Boston an isolated urban park lost 25% of its plant diversity over 100 years. To what extent greenways and corridors increase connectivity and contribute to maintain viable populations in urban green areas is poorly understood. But greenways may, in multiple ways, provide a chain of different habitats permeating the urban environment and be of benefit for many organisms. Apart from preventing local extinction and facilitating re-colonization, increased habitat connectivity is important to maintaining vital biological interactions, for example, plant–pollinator interactions and plant–seed disperser interactions. Although most of the studies in urban landscapes address the continuous loss of green areas due to urban growth and expansion, this is not the case in all cities. For example, in Shanghai the proportion of green areas has increased in parallel with urban expansion and the total area expanded from less than 9 km^2 in 1975 to more than 250 km^2 in 2005.

Gradient analyses have a long tradition in ecology and go back to the pioneering work by Whittaker in the late 1960s. Gradient analyses have also been a rather common way of disentangling the complexity of urban habitats and have been used to investigate how urbanization changes ecological patterns and processes across landscapes, for example, in invertebrate, plant, and bird community composition, leaf litter decomposition and nutrient cycling, and the structure of landscape elements. Almost all the gradients that have been used for urban studies have been one dimensional in the sense that they only describe physical features of the gradient such as proportion of impervious surface, while the characteristics of the human population occupying a particular portion of the landscape often have been neglected. Because urbanization is an exceedingly complex amalgamation of factors, by using only a single axis the interpretation of the underlying processes has often been severely constrained. It has been suggested that a more comprehensive gradient analysis should include not only physical geography, demography, rates of ecological processes, and energy, but also history of land use, socioeconomic analyses, and patterns of management.

Variation in species densities across an urban gradient suggests that some individual species disappear with urbanization, whereas other species invade in response to the environmental changes associated with development. At least for birds, species richness has often been found to peak at intermediate levels of urbanization and decrease with either more or less development. Some species are classified as urban avoiders with their highest densities at the most natural sites, whereas many species seem to be able to adapt to suburban environments, with densities peaking at intermediate levels of development. Some species are urban exploiters whose highest densities are found at the urban core (see **Fig. 2**).

A multitude of factors are likely to influence this pattern of extinction and colonization, of which changes in predation rates have been suggested to be among the most important. Predation on artificial nests has often been found to be higher in urban parks than in neighboring woodlands and the abundance of predators such as corvids, rats, and house mice are often more in urban parks compared to the rural end of the gradient. However, there are also studies showing no correlation or a declining predation pressure along the urban–rural gradient. Observed patterns of extinction and invasion in urban landscapes may also be linked to gaps in the spectrum of body masses exhibited in the community and there are documented cases that body mass patterns are correlated with invasion and extinction in other human-transformed ecosystems.

In cities, ownership and management of urban habitats is extremely diverse and complex. In addition to land managed by government, municipalities, churches, and foundations, there is also land managed by local user groups that often covers substantial tracts. For example, domestic gardens cover 23% of the land area of Sheffield, and as much as 27% of the city of

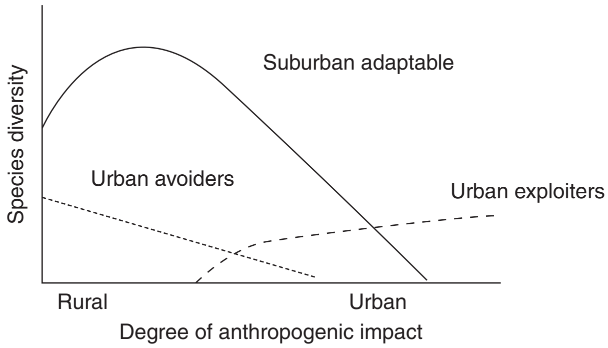

Fig. 2 Plants and animals may respond differently to increasing human impact. Urban avoiders are large-bodied species or species linked to late successional stages. These species might be very sensitive and show a decline already at moderate human impacts. Suburban adaptable speceis may, to various degrees, utilize human modifications of the landscape; the majority of plant and animal species likely belong to this group. Urban exploiters directly benefit from human presence for food, reproduction or protection, and may often be cosmopolitan, generalist species. Terminology after Blair, R.B., 1996. Land use and avian species diversity along an urban gradient. Ecological Applications 6 (2), 506–519.

Leicester. Lands appropriated for allotment areas, domestic gardens, and golf courses were found to cover nearly 18% of the total green space of greater Stockholm, Sweden, representing well over twice the area covered by nature-protected areas. While the numbers of ecological studies of urban green areas are limited, there is evidence that different types of urban green areas used for purposes other than biodiversity conservation play an important role in sustaining urban biodiversity. For example, in many cities of Asia, educational institutions sometimes harbor the largest and last remaining green areas in extensively urban developed settings. These campus areas can be extremely significant for biodiversity. A good example is the university campuses of Pune city, India, which harbor up to half the plant, bird, and butterfly species of the region despite the fact that these campuses only cover some 5% of the land area. Another illustrative case is the Musahi Institute of Technology in Yokohama, Japan, where a former community-managed forest now restored for student education, has revived interest in reducing the loss of biodiversity-rich forests in semiurban areas of Japan. Ecological studies also show that domestic gardens sometimes hold a rich flora of plants, including rare and threatened ones. Thompson and colleagues found that the private gardens in Sheffield, UK, contained twice as many plant species as any other habitat assessed. These gardens also supported surprisingly high numbers of invertebrates and this regardless of whether garden plants were native or alien. Even such a controversial land use as golf courses can contribute with important biodiversity functions in cities when courses are wisely managed and well designed. For example, golf courses contribute to sustain urban woodlands in many cities of Japan, and in some larger cities of Sweden they may harbor significant populations of species of both amphibians and macro-invertebrates, which are declining in rural areas.

Also, smaller habitat parcels in urban settings can provide high-quality habitats. One illustrative example of this is allotment areas, common in many city-regions in developed countries. For example, while allotment areas only cover some 0.3% of the land in greater Stockholm, they tend to be extremely biodiversity rich. In Stockholm city one allotment garden was found to contain 447 different plant species in an area of 400 m^2.

Urban Systems and Ecosystem Services

The concept of ecosystem services has proved to be useful in describing human benefits from urban ecosystems. For example, urban vegetation may significantly reduce air pollution, mitigate the urban heat island effect, reduce noise, and enhance recreational and cultural values, of importance for urban citizen's well-being (Table 2).

The scale of importance for generation of these services is often much larger than a city, for example, for reduction of air pollutants and water regulation, while for some, such as recreational and educational services, generation often occur within city boundaries. In most cases, these services tend to be overlooked by urban planners and decision makers, despite the fact that the potential of generation of ecosystem services can be quite substantial. In a study made within Stockholm County, it was assessed that this region's ecosystems potentially could accumulate about 41% of the CO_2 generated by traffic and about 17% of total anthropogenic CO_2. In the Chicago region, trees were found to remove some 5500 t of air pollutants per year, providing a substantial improvement in air quality. It was also found that the present value of long-term benefits from the trees of the Chicago region was more than twice the present value of costs related to planting. Moreover, wetlands in urban settings can substantially lower the amount of money spent on sewage treatment costs and in many cities large-scale experiments are taking place where wetlands are being used to treat sewage water. It has been estimated that up to as much as 96% of the nitrogen and 97% of the phosphorus can be retained in wetlands through the assimilation of wetland plants and animals. Green spaces of cities also provide ample opportunity for recreation. In a study on the response of persons put under stress, it was shown that when subjects of the experiment were exposed to natural environments the stress level decreased, whereas during exposure to built-up urban environments the stress levels remained high or even increased.

Table 2 Examples of services generated by urban ecosystems

Ecosystem services
Supporting services
Soil formation
Nutrient recycling
Provisioning services
Freshwater
Food, fiber, and fuel
Genetic resources
Regulating services
Air quality
Local climate regulation
Water purification and waste treatment
Biological control
Pollination
Cultural services
Esthetic and recreational
Educational

A major challenge in urban areas is how to sustain the capacity to generate ecosystem services. This capacity is mainly but not exclusively related to the diversity of `functional groups' of species in a system, like organisms that pollinate, graze, predate, fix nitrogen, spread seeds, decompose, generate soils, modify water flows, open up patches for reorganization, and contribute to the colonization of such patches. In urban areas, such functional groups may be substantially reduced in size or show changes in the composition due to high species turnover, both of which may increase vulnerability in maintaining ecosystem services. To what extent exotic species contribute to reduce or enhance the flow of ecosystem services is virtually unknown for any urban area. But, since introduced species make up a large proportion of the urban biota, it is important to know not only to what extent introduced species are detrimental, but also to what degree some of the introduced species may enhance local diversity and maintain important functional roles. For urban ecology to significantly contribute to improving management of urban habitats and the maintenance of ecosystem services, the following research questions are particularly urgent to address:

- To what extent are urban ecosystems sinks for many animal and plant species and what are the effects of species loss on ecosystem functions?
- To what extent do novel species play important functional roles in urban ecosystems by replacing role of extinct native species and enhancing ecosystem functions and services?
- What is the importance of source–sink dynamics and matrix permeability for maintenance of urban biodiversity and important ecosystem services?
- How do we develop management systems that match the spatial and temporal scales of ecological processes?

Urban Restoration

Designed, replicated urban restoration experiments could substantially advance our knowledge and understanding of processes of importance for generating urban ecosystem services, for example, through better understanding of population and community responses to disturbances, patterns of self-organization and succession, assembly rules, and through identifying components that contribute to resilience or vulnerability. Urban restoration also represents an interesting opportunity for ecologists to work in partnership with landscape architects, urban designers, and architects and help in designing urban environments based on ecological knowledge but merged with the functional and esthetic design of urban space.

The majority of urban restoration projects deal with transforming brown areas (abandoned industrial lots or air fields, landfills, etc.) to functioning green areas, such as Fresh Kills landfill on Staten Island, New York, or the Olympic Park in Beijing. Other large-scale restoration projects involve, for example, substantial wetland restoration such as Kristianstad, Sweden, and New Orleans, USA. In New Orleans, coastal wetlands have eroded substantially during the last 50 years and restoring wetlands is viewed as one important measure to reduce vulnerability to hurricanes. Important lessons of urban restoration projects so far are that restoring ecological functions in urban areas is possible but time consuming and that there are often significant effects on many ecosystem services even after one or two seasons. Although the costs are initially high, these could be offset by increases in property values and increased investments in development in areas surrounding the restoration site.

Urban Landscapes as Arenas for Adaptive Management

In cities that experience rapid social and environmental transformation, it is critical to develop a capacity to respond to potential surprises. One important aspect of such capacity building is to facilitate for a wider integration of local people and interest groups in the use and management of urban green areas. There are several reasons for a wider integration of local people in urban ecosystem management. First, governments cannot entirely rest on protected area management to safeguard the native flora and fauna found in city-regions. As cities expand, there will be an increased lack of natural lands for the establishment of protected areas. Studies also show that many urban nature reserves are unable to sustain native species in the long run. In addition, protected area management is financially costly to most local governments. In London, for example, parts of the protected green belt have been severely degraded due to lack of money and this has resulted in urban residents avoiding these areas for various activities. Second, much of the flora and fauna depend on well-functioning habitats provided by privately owned lands. In the US, for example, almost two-thirds of all the endangered and threatened species depend on private lands for their continued existence. Also, urban homeowners with gardens have been engaged to support declining pollinator populations in Great Britain through the deliberate planting of certain nectar providing plants in their yards. They have also helped sustain urban frog populations during their period of main rural declines through a massive establishment of garden ponds. Homeowners in Britain are also involved in programs for monitoring trends in the population status of birds. Third, a number of international treaties that have been signed by national governments around the world, including local Agenda 21, the Convention of Biological Diversity, and the Malawi-principles, strive toward a decentralization of biodiversity management down to local people. Recently, the Millennium Ecosystem Assessment (MA 2005) concluded that a wider cooperation among people within different sectors in society is necessary for more efficient land use that contributes to the support of ecosystem services.

One approach increasingly used to achieve collaborative partnership in urban ecosystem management is `adaptive co-management'. The approach rests on the notion of the sharing of resource management responsibility and authority between users of ecosystems and government agencies. This typically involves local people and interest groups, scientists and local authorities, with the potential to promote information exchange to effectively deal with and respond to change and issues that often transcend locality. Adaptive co-management emphasizes `learning-by-doing' in ecosystem management, where management objectives are treated as `experiments' from which people can learn by testing and evaluating different management policies. This form of ecosystem management avoids set prescriptions of management that may be superimposed on a particular place, situation, or context. Such designs have the potential to lower overall costs of management, most notably costs incurred for describing and monitoring the ecosystem, designing regulations, coordinating users and enforcing regulations, and depend on the self-interest of participants. Co-management arenas could, for example, also serve as platforms for designed experiments and urban restoration as discussed above and improve ecological functions and designs in cities.

Linking Humans and Nature in the Urban Landscape

Urban landscapes are not only ecological experiments but also long-term experiments in social, economic, and cultural transformations shaped by cultures, property rights, and access rights. Since cities are places where knowledge, human and financial resources are concentrated, rapid urban transformations can likely be more readily monitored and observed than similar processes in more rural areas. Studies of transformations in urban landscapes may therefore well provide the ground for a better understanding of socio-economic drivers of changes also in other ecosystems. After decades of mutual neglect and artificial divide between nature on the one hand, and cities with their respective urban processes on the other hand, the conservation community has started to shift its perception to include cities as a component of natural landscapes. Just as it is now increasingly recognized that in protected nature reserves, conservation will not be successful as long as it is at the expense of human aspirations, urban planners increasingly acknowledge that functioning natural systems such as watersheds, mangroves, and wetlands are indispensable for reducing vulnerabilities to natural disasters and building long-term resilience.

In New Orleans for example, it has been argued that population growth and urban economic growth is necessary for meeting the costs of building a viable defense against the grave environmental problems of massive coastal erosion. In the New York Metropolitan region, sustainable management of the Catskills, the land around the upland water reservoirs supplying New York City with drinking water, has been chosen as an important complement to building water treatment plants.

The urban landscape provides a public space for the cross-fertilization of minds and various disciplines, enabling a new perspective on man in nature, one that could place human well-being at the core, break the artificial and largely culturally biased divide between the pristine and the human-dominated ecosystems, and contribute to the creation of a new language, with signs, concepts, words, tools, and institutions that would gather rather than divide, broker conflicts rather than create them, and establish responsible environmental stewardship at the heart of public interest.

See also: Ecological Complexity: Citizen Science. Ecological Data Analysis and Modelling: Spatial Models and Geographic Information Systems. Global Change Ecology: Urbanization as a Biospheric Process: Carbon, Nitrogen, and Energy Fluxes. Human Ecology and Sustainability: Industrial Ecology; Urban Metabolism. Terrestrial and Landscape Ecology: Landscape Planning; Anthropogenic Landscapes; Landscape Ecology

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