SPRINGER SERIES ON ENVIRONMENTAL MANAGEMENT

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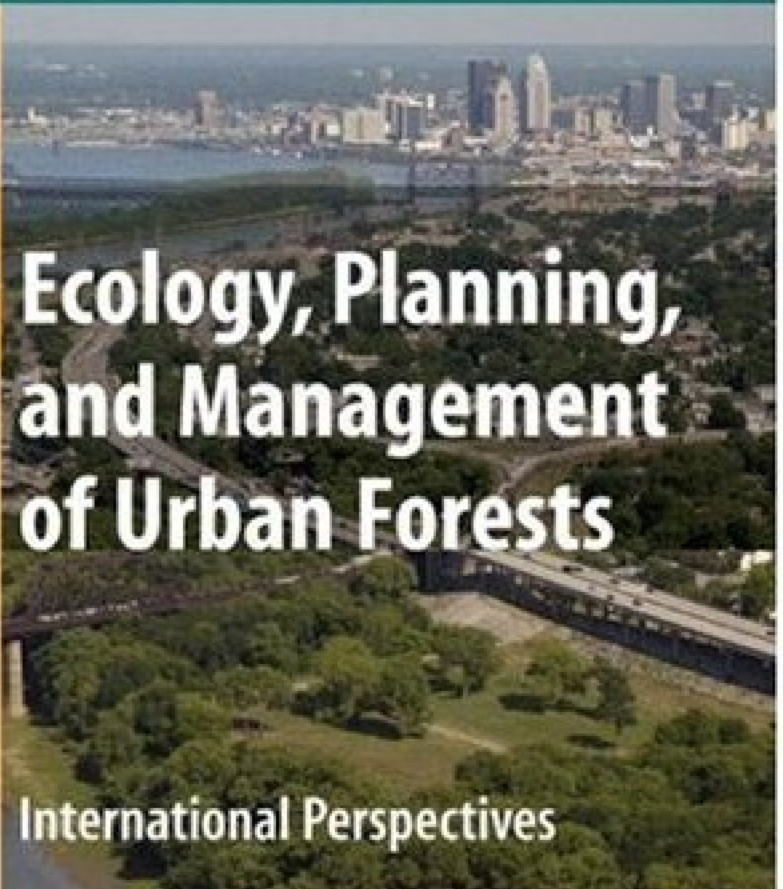

Ecology, Planning, and Management of Urban Forests

International Perspectives

Springer

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Toward a Landscape Ecology of Cities: Beyond Buildings, Trees, and Urban Forests

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Human population growth and urbanization are two dominant demographic trends in our time (Brown, 2001). World population has continued to grow exponentially for the past several decades, and reached 6.2 billion in 2002, with a current annual increase rate of almost 80 million (Earth Policy Institute, 2002). The proportion of the total world population that is urban was only a few percent in the 1800s, but it increased to 14% by 1900, rapidly jumped to about 30% in 1950 (Platt, 1994a; Wu and Overton, 2002), and is passing 50% now. Evidently, as the world's human population has increased exponentially, so has the proportion of people living in cities (Fig. 2.1). It has been projected that 60% of the world's population will reside in urban areas by 2025 (Platt, 1994a). In 1800, there was only one city, Beijing, in the entire world that had more than a million people; 326 such cities existed 200 years later (Brown, 2001). The urban population is growing three times faster than the rural population (Nilsson et al., 1999), and we are now witnessing a historically unprecedented and monumental, global-scale, rural-to-urban transition. To quote Lester Brown (2001), "For the first time, we will be an urban species!"

At a more regional scale, urban people already account for more than two thirds of the European population today. In the United States, 74% of the population resided in urban areas in 1989, and this number will increase to more than 80% by 2025 (Pickett et al., 2001). The historical record so far has shown that both the number of mega-cities as well as the number of urban dwellers have increased much faster in developing countries than in developed countries. For example, nearly 40% of the population of the Asia-Pacific region is now urban, and the region contains 13 of the 25 largest cities of the world. It has been estimated that by 2015 about 903 million people in Asia will live in cities with a population of over one million people (cf. Wu and Overton, 2002). While the world's urban population is projected to rise to 60% by 2025, nearly half of these people will reside in the Asia-Pacific region. Undoubtedly, urbanization will continue to have significant impact on the environment as well as on economic, social, and political processes at local, regional, and global scales.

Urbanization has profoundly transformed many natural landscapes throughout the world, and contributed significantly to the current crisis of biodiversity loss and deterioration of ecosystem services. Although cities cover less than 2% of the

M.M. Carreiro et al. (eds.), *Ecology, Planning and Management of Urban Forests: International Perspectives*.

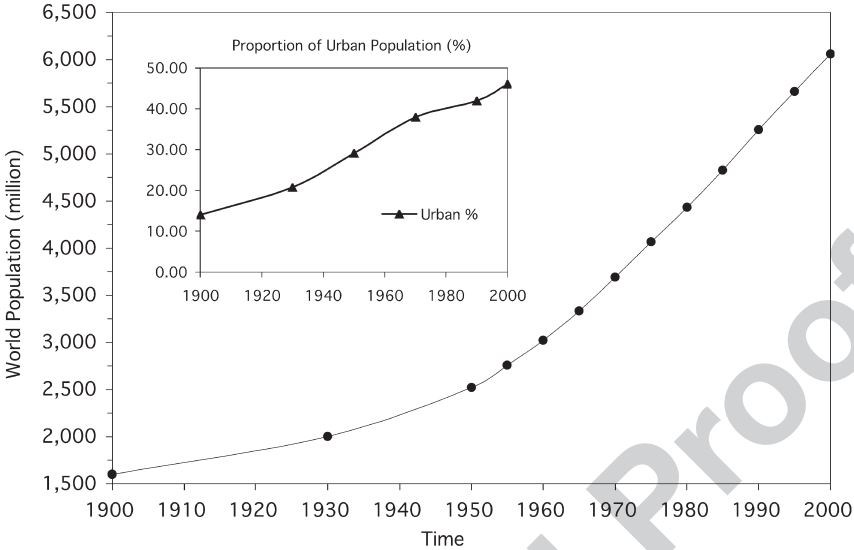

Fig. 2.1 Increase in the total world population and the proportion of the urban dwellers in the 20th century (1900–2000). Data were from United Nations (2001), Platt (1994a), and World Resources Institute (1998)

earth's land surface, they account for 78% of carbon emissions, 60% of residential water use, and 76% of the wood used for industrial purposes (Brown, 2001). About half of the world's nitrogen fixation is mediated by humans (Galloway, 1998), and the ecological impacts of urbanization in terms of biodiversity, biogeochemistry, and ecosystem services go far beyond the city limits. Also, rapid urbanization since the 1990s has been accompanied by a proliferation of slums and dysfunctional neighborhoods with high health risks, especially in most developing countries. High rates of urbanization and industrialization have increased the demands for land, water, and energy, and resulted in expanding transportation networks that constitute a key accelerating factor in economic growth as well as environmental degradation. Urbanization in many countries has resulted in air and water pollution, loss of productive agricultural land, loss and fragmentation of species habitats, overextraction of groundwater resources, and deforestation as a consequence of increased demand for construction timber. The most serious air pollution problems often occur in urban areas. A survey by the World Health Organization (WHO) and United Nations Environment Program found that the levels of suspended particulate matter (SPM) in 10 of the 11 cities they examined were two times higher than WHO's guidelines for protecting human health. It is important to realize that the ecological influences of cities go far beyond the space they occupy. Urban ecological footprints can be enormous because of their huge demands for energy, food, and other resources, and the regional and global impacts of their wastes and emissions on soil, air, and water (Wackernagel and Rees, 1996; Rees, 1997; Luck et al., 2001; Wu and Overton, 2002). For example, London's population consumes some 55,000 gallons of fuel and some 6600 tons of food, and emits 160,000 tons of carbon dioxide (CO_2) every single day. Such consumption requires a land base 12.5 times the size of London to support its population (Beatley, 2000). Vancouver's ecological footprint was estimated as being 180 times that of its city size (cf. Collins et al., 2000).

Clearly, cities are places where people are most concentrated, and where environmental problems are most devastating. Although there are apparently a myriad of political, socioeconomic, and environmental causes and consequences of urban problems, it is certain that to alleviate these problems our cities must be designed, planned, and managed in a more ecologically sound manner. Up until now, urbanization has, for the most part, increasingly isolated humans from nature through artifacts and technology. But it is clear that if an agreeable human quality of life is to be sustained in urban systems, then the ecological state of its natural components must be improved and harmony between people and nature must be set as a goal. In short, sustainable cities are most likely to be ecologically sound cities—eco-cities. To achieve the ecological integrity of cities, urban forests and other types of green spaces are critically important, and they must be explicitly and adequately considered in the design, planning, and management of urban systems. This chapter reviews some of the changing perspectives and approaches in urban ecology, and outlines several key concepts and principles in landscape ecology that are relevant to the research and practice of urban forestry and the development of eco-cities.

Urban Forests and Their Values

The urban forest usually refers to all woody plants in and around the city, including street trees, yard trees, park trees, and planted or remnant forest stands (Miller, 1997; Helms, 1998; Konijnendijk, 1999). Many studies have documented that urban forests may have a number of ecological/environmental, economic, and sociocultural benefits. For example, urban forests can improve air quality by absorbing particulates and pollutants (e.g., ozone, chlorine, sulfur dioxide, nitrogen dioxide, fluorine), sequester atmospheric CO_2, reduce soil erosion and purify water, serve as habitats for plants and animals, alleviate noise pollution, moderate local/regional climate to save energy consumption (i.e., reducing urban temperature in summer and heat loss in winter), increase real estate values, improve neighborhood and landscape aesthetics, and enhance the psychological well-being of urbanites (Burch and Grove, 1993; Platt et al., 1994; Miller, 1997; Kennedy et al., 1998; Nilsson et al., 1999).

Some of the ecological and socioeconomic values of urban forests are quite impressive, and may even sound astounding to traditional ecologists. For example, according to a report by the United States Department of Agriculture's (USDA) Center for Urban Forest Research (USDA/CUFR, 2002), parking lot trees in Davis, California, reduced the surface temperatures of asphalt by as much as 20°C (36°F), and cabin temperatures of vehicles by over 26.1°C (47°F). The parking lot trees in Sacramento, California, with an overall 8.1% effective shade area, generated annual benefits of $700,000/year, and increasing the shade to 50% will boost the benefits to $4 million/year (McPherson et al., 1999; McPherson, 2001; USDA/

CUFR, 2002). Data from 31 California cities showed that air temperature was warming due to the urban heat-island effect at a rate of 0.4°C (0.72°F) per decade since 1965 (Akbari et al., 1992), while the increase rate of downtown temperatures for the entire United States has varied from 0.14° to 1.1°C (0.25° to 2°F) per decade since the 1950s (McPherson, 1994). This urban warming had direct economic and energy use consequences. McPherson (1994) estimated that about 3% to 8% of electric demand in the U.S. was used to compensate for the urban heat-island effect. A cost-benefit analysis of energy-efficient landscaping with trees in Tucson, Arizona, estimated that the net benefits for planting 500,000 trees was $236.5 million for a 40-year planning horizon; computer simulations projected that an additional 100 million mature trees in U.S. cities could save 30 billion kilowatt-hours of energy for heating and cooling, and consequently reduce CO_2 emissions by as much as 8 billion kilograms (8 million metric tons) per year (cf. McPherson, 1994).

Urban forest benefits are not just economic. The following classic example demonstrates the psychological and health-improvement value of urban forests. Ulrich (1984) examined the records for 1972 to 1981 for recovery of 46 patients after gallbladder surgery in a suburban Pennsylvania hospital to determine whether a window view with or without trees might have any restorative influences. The results showed that the 23 patients who could view a small stand of deciduous trees from their room windows had significantly shorter hospital stays, received fewer negative evaluative comments in nurses' notes, and took fewer painkillers than the other 23 who had windows facing a brown brick wall. Wilson (1984) and Kellert and Wilson (1993) argued that people, when isolated from nature, will suffer psychologically, which may lead to a measurable decline in well-being—the biophilia hypothesis. Other empirical studies corroborate this hypothesis (Roszak et al., 1995; Brown, 2001). Given all these measurable social and economic benefits, urban forests (and all urban green spaces) should be properly maintained, planned, and managed. However, all the ecological and socioeconomic functions have not been well studied by scientists, and are not well known to the public. Consequently, municipal budget allocations to green space and urban forestry are often smaller than needed for their maintenance.

To enhance more integrative research and promote values of urban forestry, it is necessary to broaden the concept of urban forestry. Urban forestry is closely related to "community forestry" and "social forestry" (Miller, 1997; Nilsson et al., 1999). Traditionally, the study of urban forests has focused primarily on local-scale and applied issues (Konijnendijk, 1999), and urban forests are often managed as individual trees instead of from the perspective of a whole forest ecosystem (University of Florida/Institute of Food and Agricultural Sciences, 2001). However, since any urban environment is extremely heterogeneous in space and dynamic in time, and since areas containing urban trees and forest patches are often geographically fragmented, an urban forest may be most appropriately treated as a landscape that consists of a variety of changing and interacting patches of different shape, size, and history. Urban trees and forests are integral parts of this urban landscape—a dynamic patch mosaic system. As a science of the relationship between spatial heterogeneity and ecological processes, therefore, landscape ecology provides many useful concepts and principles for urban planning and design in general and for urban forestry in particular, as will be explained below.

Changing Perspectives in Urban Ecology

A major goal of urban ecology is to understand the relationship between the spatiotemporal patterns of urbanization and ecological processes. Thus, the study of urban morphology and its evolution is critically important. As early as 1825, the German economist von Thünen asserted that the urban morphology of an isolated city would be characterized by concentric economic rings (e.g., business, residential, industrial, agriculture), as dictated by simple cost-benefit relations (the principle of marginal spatial utility; cf. Portugali, 2000). Von Thünen's work laid an important foundation for the theory of urban development, including the concentric zone theory and the central place theory, which depict cities as more or less concentric or symmetric structures with one or more central business districts (CBDs). In contrast with the concentric-ring models, the sector theory allows for corridors or wedges of industrialization due to the influence of transportation networks. The multiple nuclei theory recognizes the multiple centers of specialized activities (e.g., finance, industry, commerce, residence) and describes an asymmetric patch mosaic pattern. These theories of urban forms are commonly found in textbooks in social sciences, and represent the exceptions rather than the norm when applied to real cities. In particular, the concentric zone theory, the sector theory, and the multiple nuclei theory were developed based primarily on studies of American cities (Chicago, San Francisco, and Boston, respectively) several decades ago, and thus they are less applicable to cities in other countries or even to most young American cities (Thio, 1989).

Cities may differ drastically in their architectural appearance and environmental settings, but one commonality is that the diversity and spatial arrangement of their landscape elements undoubtedly affect and are affected by physical, ecological, and socioeconomic processes within and beyond their boundaries. Ecologists have long studied the effects of spatial pattern of urbanization on ecological processes (Stearns and Montag, 1974; Sukopp, 1990, 1998; Loucks, 1994; Breuste et al., 1998; Zipperer et al., 2000). In fact, urban ecological studies date back several decades ago when botanists, notably of the Berlin school of urban ecology (Sukopp, 1990, 1998), documented the spatial distribution of plants in and around cities. In contrast, the Chicago school of urban ecology defined the field as the study of the relationships between people and their urban environment by applying concepts developed in plant and animal ecology, most prominent of which are concepts of dominance, competition, invasion, and succession (Thio, 1989). Apparently, this view of urban ecology is a subdiscipline of social or human ecology and focuses more on people rather than on biological organisms and their organization within cities.

Based on the degree of emphasis and reliance on biological ecology as well as conceptual and methodological frameworks, I distinguish five urban ecological approaches (Fig. 2.2). These approaches are essentially developed from three broad

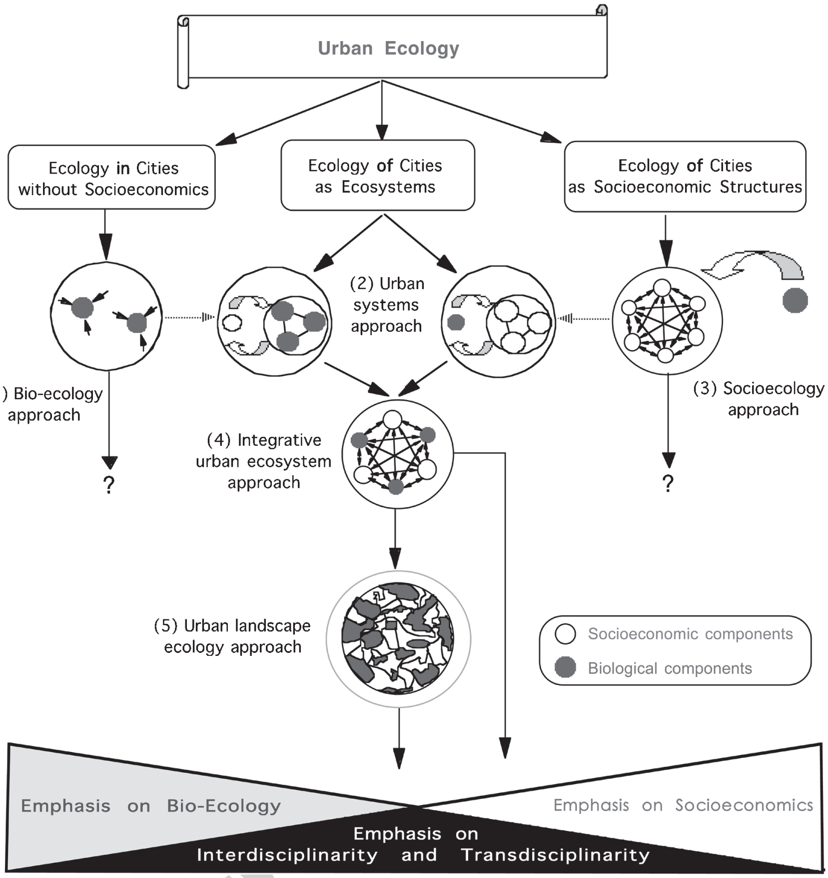

Fig. 2.2 Development of different perspectives in urban ecology. In general, there has been an evolution of perspectives from the ecology *in* cities to the ecology *of* cities, from isolated organismal to landscape studies, and from disciplinary investigations to interdisciplinary integration. See text for more detail

perspectives on urban ecology: ecology in cities (the first approach), ecology of cities as socioeconomic structures (the second approach), and ecology of cities as ecosystems (the third to fifth approach). The first approach focuses solely on the ecology of plants and animals living in urban areas, assuming that this can be accomplished without explicitly considering socioeconomic causes and consequences. This approach leads to what may be called the bio-ecology perspective (Fig. 2.2). In sharp contrast, the second approach treats cities as socioeconomic structures or organizations. It tackles complex urban social and economic patterns and processes by applying some concepts and principles from biological ecology, while, ironically, biological organisms and their associations (populations and communities) within cities are overlooked. This approach leads to the so-called socioecology perspective (Fig. 2.2). Obviously, both of these approaches capture only certain components of the urban system, but neither of them singly is adequate to understand the city as a society–nature interactive system where components affect each other.

The third approach considers the city as an urban system that is composed of both socioeconomic and biological components (Fig. 2.2). While this approach seems to combine some of the elements in the previous two approaches, it is characterized mainly by the systems methodology that emphasizes causal relations, feedback, and various interactions among system components. This urban systems perspective focuses either on socioeconomic dynamics (e.g., Forrester, 1969) or ecological processes (e.g., Stearns and Montag, 1974). Although both ecological and socioeconomic components are recognized here, they are not well balanced and integrated. Further integration between the bioecology and socioecology perspectives and between human ecology and ecosystem ecology has led to the fourth approach, the integrative urban ecosystem approach (Fig. 2.2). An example of this is Zev Naveh's total human ecosystem (Naveh and Lieberman, 1984). This is really an urban ecosystem perspective in that it treats both the biological and socioeconomic components of the city as equally important and in an integrative rather than divisive manner (also see Pickett et al., 1997). Finally, over the past two decades with the acutely growing awareness of the importance of considering spatial heterogeneity and its ecological consequences for understanding system processes, the urban landscape ecology approach has emerged (Fig. 2.2). This landscape approach emphasizes not only the diversity and interactions of the biological and socioeconomic components of the city, but also the spatial pattern of these elements and their ecological consequences from the scale of small patches to that of the entire urban landscape, and to the regional context in which the city resides (Pickett et al., 1997; Zipperer et al., 2000; Luck and Wu, 2002; Wu and David, 2002). Several contrasting characteristics of these different perspectives and associated approaches are summarized in Table 2.1.

Urban planning and design also seem to have experienced a paradigm shift in the past one-and-a-half centuries. For example, Platt (1994b) provided a lucid discussion on how the concepts of open space in North American cities have evolved in relation to urban design and planning. The "Picturesque Rurality" favored "the establishment of large, lavishly planted urban parks," but "put less emphasis on functional utility than on aesthetic effect through landscape design and horticulture"; the "City Beautiful" monumentalism "emphasized large, geometric plazas embellished with fountains, statuary, and formal landscaping;" the "Garden City" notion advocated having open spaces of different forms (e.g., practical community parks and individual garden plots) as major elements of the city and throughout the core of the city (Platt, 1994b). Although the City Beautiful and Garden City were among the most influential paradigms in urban design and planning, it is evident that modern urban designing and planning principles have moved beyond an initial focus on city form and human interests. Efforts by urban planners, designers, and architects to combine urban morphology with ecological functioning and efforts by ecologists to integrate the "ecology in cities" with

Table 2.1 Different perspectives on urban ecology, corresponding research approaches, and their major characteristics

Perspectives on urban ecology	Ecology in cities without socioeconomics	Ecology of cities as ecosystems	Ecology of cities as socioeconomic structures
Approaches to studying urban ecology	• Bioecology approach	• Urban systems approach • Integrative urban ecosystem approach • Urban landscape ecology approach	• Socioecology approach
Major characteristics	• Urban areas disturbed as environment	• Cities as unique ecosystems	• Cities as socioeconomic systems
	• Basic ecology in urban environment	• Humans as integral components of landscape systems	• Humans as the primary or the only system components
	• Humans as disturbance agents	• Consideration of both ecological and socioeconomic patterns and processes	• Ecological principles and methods used only as metaphors
	• Spatiotemporal patterns of organisms and human influences	• Problem-solving and solution-driven research	• Dominated by methodologies developed in social sciences
	• Non–solution-driven research	• Strong interdisciplinary interactions between natural and social sciences	• Little cross-disciplinary interactions between natural and social sciences
	• Little cross-disciplinary interactions between natural and social sciences		

Note: See Fig. 2.2 for a schematic representation of how these different perspectives and approaches evolve and relate to each other.

socioeconomic patterns and processes have brought both sides much closer to a common perspective—a landscape ecological perspective of cities.

In the next section, I shall discuss the major elements of landscape ecology and explore how landscape ecological principles may be used for improving the research and practice of urban forestry.

A Landscape Ecology Perspective on Cities

What Is Landscape Ecology?

Landscape ecology is the science and art of studying and influencing the spatial pattern of landscapes and its ecological consequences. The "science" of landscape ecology provides the theoretical basis for understanding the formation, dynamics, and ecological effects of spatial heterogeneity, and the relationship between landscape pattern and ecological and socioeconomic processes over different scales in space and time. The "art" of landscape ecology reflects the humanistic perspectives necessary for integrating biophysical and socioeconomic and cultural components within the landscape in general, and landscape design, planning, and management in particular. The term *landscape ecology* was coined by Carl Troll (1939), a German geographer. Before the early 1980s, landscape ecology was essentially a regional applied science, practiced mainly in Europe and focusing on land planning and human–ecosystem interactions (Naveh and Lieberman, 1984). The globalization of landscape ecology started with a series of publications in North America (Forman and Godron, 1986; Moss, 1988; Turner, 1989; Turner and Gardner, 1991). In the past two decades landscape ecology has experienced unprecedented rapid development in both theory and applications, and established itself as both a field of study and a new ecological paradigm (Wu and Loucks, 1995; Wu, 2000).

Based on the views of a group of leading landscape ecologists, Wu and Hobbs (2002) summarized six key issues that define the scope of landscape ecology: (1) interdisciplinarity or transdisciplinarity, (2) integration between basic research and applications, (3) conceptual and theoretical development, (4) education and training, (5) international scholarly communication and collaborations, and (6) outreach and communication with the public and decision makers. The terms of *interdisciplinarity* and *transdisciplinarity* have been defined variously in the literature, but I find the definitions summarized by Tress et al. (2005) both clear and satisfactory. Interdisciplinary research involves multiple disciplines that have close cross-boundary interactions to achieve a common goal based on a concerted framework, thus producing integrative knowledge that cannot be obtained from disciplinary studies. On the other hand, transdisciplinary research involves both cross-disciplinary interactions and participation from nonacademic stakeholders or governmental agencies guided by a common goal, thus producing integrative new knowledge and uniting science with society (Tress et al., 2005).

The six key issues are all related to each other, and may be important to sciences other than landscape ecology. But the emphasis on beyond-bioscience interdisciplinarity and real-world problem solving is one of the several characteristics distinguishing landscape ecology from the traditional bioecological disciplines such as population or community ecology. Because the structure and functioning of landscapes are influenced by a myriad of physical, biological, socioeconomic, cultural, and political forces, the ecology of landscapes must be interdisciplinary. This is necessary for landscape ecology to provide the scientific basis for resource management, land use planning, biodiversity conservation, and other broad-scale environmental issues. The same group of landscape ecologists also identified a list of top research topics in the field: (1) ecological flows in landscape mosaics; (2) causes, processes, and consequences of land use and land cover change; (3) nonlinear dynamics and landscape complexity; (4) scaling and uncertainty analysis; (5) methodological development; (6) relating landscape metrics to ecological processes; (7) integrating humans and their activities into landscape ecology; (8) optimization of landscape pattern; (9) landscape conservation and sustainability; and (10) data acquisition and accuracy assessment (Wu and Hobbs, 2002).

In essence, landscape ecology is a highly interdisciplinary field of study that focuses on spatial patterning of landscape elements and its relationships to ecological processes on different scales in space and time. No matter which aspects of the landscape one may concentrate on, be they biophysical, socioeconomic, or both, the landscape ecological paradigm helps bring the phenomena into perspective by integrating pattern, process, scale, and hierarchy. The key issues and research topics seem equally relevant to the science and practice of urban forestry and ecological cities. In particular, I suggest that the several principles discussed below may be used to guide the planning, managing, and design of urban forests and eco-cities.

Landscape Ecological Principles for Urban Forestry and Eco-Cities

Hierarchy Theory of Landscapes

Landscapes are nested hierarchical systems in both structure and function (Miller, 1978; Haigh, 1987; Urban et al., 1987; Wu and Loucks, 1995; Wu, 1999; Bessey, 2002). A hierarchy or hierarchical system can broadly be defined as a partial ordering of interactive entities (Simon, 1973). In hierarchical systems, higher levels are characterized by slower and larger entities (or low-frequency events), and lower levels are characterized by faster and smaller entities (or high-frequency events). The upper level exerts constraints (e.g., as boundary conditions) to the lower level, whereas the lower provides initiating conditions to the upper (Wu, 1999). Hierarchy theory suggests that when one studies a phenomenon at a particular hierarchical level (the focal level, often denoted as level 0), the mechanistic understanding comes from the next lower level (level −1), whereas the significance of that phenomenon can only be revealed at the next higher level (level +1).

The urban forest clearly forms a nested spatial hierarchy: individuals trees, tree corridors (e.g., trees along streets and roads), and networks (e.g., trees around parking lots, residential and urban blocks), patches of different shape and size (e.g., trees as aggregates in parks or remnant or planted forest fragments), and the entire urban forest in and around the city that also includes other types of green spaces (e.g., lawns, golf courses, and shrub communities). Clearly, urban forest planning, management, and designing should not stop at the urban fringe. This hierarchical view suggests that a fuller understanding and appreciation of urban forests can be gained by considering them at multiple scales. We need to see the trees, the forest, the corridors, the patches, the urban landscape, and the regional context, as well as understanding the hierarchical linkages among all of them!

Pattern-Process Principle

An important principle in landscape ecology is that the spatial pattern affects and is affected by ecological processes, and that the relationship between pattern and process is scale dependent. Here "pattern" includes both the composition (e.g., the number and abundance of land cover types) and configuration (e.g., the shape and spatial arrangement of landscape elements) of the landscape. "Scale" refers to the grain size (e.g., the spatial or temporal resolution of an observation set) or the extent (e.g., the total area or time duration of a study). The role of scale is ultimately important for understanding the relationship between pattern and process. If the spatial pattern changes much more slowly than the process under consideration (e.g., regional topography versus population dynamics of an animal species), the pattern-process relationship is mostly one directional: pattern affects process. However, when pattern and process are within the same spatial domain and operate on similar time scales, the pattern-process relationship is interactive. For example, the fine-scale spatial pattern of species composition and biomass in a grassland is interactive with the grazing process by cattle. The pattern affects the grazing behavior, and grazing immediately modifies the pattern and creates new patterns. Of course, in the case of overgrazing, the pattern can be totally destroyed, and a relatively homogeneous degraded or even desertified land is left behind.

The pattern-process principle certainly has implications for urban forestry and eco-cities. For example, the large-scale patterns of geomorphology, hydrology, and socioeconomic factors in an urban area set constraints on ecological processes, and thus determine where urban forests may be best maintained or planted, but local soil conditions are more likely to determine how well individual trees grow. For a variety of ecological and socioeconomic purposes, it is not only the diversity and the total amount of urban trees and forests that are important, but also the shape and spatial arrangement of individual trees and forest patches. In addition, the planning and designing of urban forests and the city as a whole must consider the multiple and sometimes conflicting ecological and socioeconomic purposes at different scales.

Landscape Connectivity

Landscape connectivity refers to the degree of connectedness among landscape elements (patches, corridors, and matrix) of the same or similar type (e.g., forest habitats, lakes, or rivers). Landscape connectivity includes both structural and functional components. Structural connectivity measures how spatially connected landscape elements are, whereas functional connectivity measures how connected an ecological process (e.g., dispersal, nutrient dynamics) is in space over a certain time scale. Clearly, landscape connectivity is dependent on both the scale of observation and ecological processes under consideration. Even for the same landscape, its connectivity may vary radically when different processes are considered (e.g., beetle movement, bird flying, seed dispersal, fire spread). With the accelerating human dominance of the earth system, landscapes have been increasingly fragmented, and wildlife habitats have been reduced in the total amount and disconnected in spatial pattern. Thus, a central question in conservation biology and landscape ecology is how landscape connectivity of habitats affects biodiversity and ecosystem processes.

Landscape connectivity is closely related to the structural and functional attributes of corridors and networks (Forman, 1995). Corridors are linear landscape elements that may function as habitats (e.g., riparian ecosystems, vegetated corridors), conduits (e.g., vegetated strips, roads), filters/barriers (e.g., windbreaks, roads), sources (areas that give off materials), or sinks (areas that receive materials). Corridors of the same or similar types interconnect to form a network, whose functionality is determined by network density (the amount or abundance of corridors), network connectivity (the degree to which all corridors are connected), and network circuitry (the degree to which loops or circuits are present in the net) (Forman and Godron, 1986; Forman, 1995). In general, corridors are undoubtedly important landscape elements. But the exact role of corridors of a particular type can only be understood with respect to the species or ecological process under consideration and, again, these will change with scale. In the past decade, the concept of landscape connectivity in terms of corridors and networks has increasingly been applied in nature conservation, resource management, and land-use planning (Noss, 1987; Cook, 1991; Cook and van Lier, 1994; Poiani et al., 2000; Opdam et al., 2001).

Percolation theory has been particularly useful for understanding landscape connectivity both structurally and functionally (Gardner et al., 1987, 1992; With and Crist, 1995). Percolation theory is the basis for studying the flow of liquids through material aggregates. In the context of landscape ecology, percolation may refer to the spread of any process through connected structural elements across the landscape. The most intriguing feature of percolation theory is the existence of a critical density of landscape components at which landscape function abruptly changes (Green, 1994; Turner et al., 2001). For example, a model landscape in which habitat and nonhabitat pixels are randomly distributed essentially has no clusters spanning across the entire landscape before the total percent habitat cover reaches the critical density or percolation threshold of $P_c = 59.28\%$. However, once the threshold is approached or exceeded, the probability of forming spanning clusters jumps to 100%, implying that much of the landscape is functionally connected (Green, 1994; Turner et al., 2001). Thus, percolation theory suggests that there are connectivity thresholds that significantly influence the flows of energy, materials, and organisms across the landscape mosaics of various kinds. Empirical studies have shown that real landscapes, most of which are clumped, often have a lower critical density value than the theoretical one predicted by percolation theory, and that landscape connectivity is a function of both the structural interconnectedness and the behavioral or dynamic features of the phenomenon.

How does this knowledge inform our thinking about urban forests? Urban forests typically contain many scattered individual trees, narrow strips, and small patches. Simply put, they are highly fragmented and often geographically disconnected. To enhance the benefits that can be derived from their ecological and socioeconomic functions, it is important to maintain a proper degree of connectivity among the different components of the urban forest across a range of spatial scales. At the same time, it is important to bear in mind that increased connectivity may also promote the spread of exotic species, epidemics, and disturbances such as fires. Overall, the concepts and knowledge of connectivity, corridors, networks, and percolation thresholds developed in landscape ecology may be useful for planning, managing, and designing urban forests as well as eco-cities.

Metapopulation Theory

In fragmented landscapes, biological populations live in geographically distributed habitat patches. A metapopulation is a system of such local populations spatially separated by unsuitable environments but still functionally and genetically connected by dispersal. Thus, metapopulations integrate the structurally nested habitat hierarchy with functionally dynamic population processes. Two salient characteristics of metapopulations are frequent local species extinction at the habitat patch level and species recolonization at the habit patch mosaic (or landscape) level. Metapopulation theory predicts that species that are locally unstable can still persist at the landscape (or regional) scale if the connectivity among habitat patches is beyond some threshold value (Opdam, 1991; Wu et al., 1993). How exactly the spatial pattern of habitat patches and corridors affects the local extinction, regional recolonization, and eventually persistence of species is a central question of metapopulation dynamics (Hanski and Gilpin, 1997; Hanski, 1999; Opdam et al., 2001).

As mentioned earlier, urban forests are a hierarchical patch dynamic system (Wu and Loucks, 1995; Wu, 1999), and may be viewed as a metapopulation when the focus is on the population dynamics and species persistence of trees in vegetated habitats. This metapopulation view becomes even more appropriate and necessary when animal species are considered. Conceptually, this is a special case of the more general hierarchical perspective of urban forestry outlined above (see Hierarchy Theory of Landscapes).

Landscape Self-Organizing Complexity

Landscapes are complex spatial systems in which heterogeneity, nonlinearity, and contingency are the norm. Findings in the sciences of complexity and nonlinear dynamics suggest that spatially extended complex systems like landscapes are often self-organizing (Perez-Trejo, 1993; Lobo and Schuler, 1997; Aber et al., 1999; Phillips, 1999). Self-organization is the capacity of complex systems to develop and change internal structures spontaneously and adaptively in order to cope with or manipulate their environment (Cilliers, 1998; Levin, 1999). Self-organizing systems tend to increase their complexity in time, and are replete with emergent properties, phase transitions, and threshold behaviors. Several inferences have emerged from this self-organizing complexity perspective: (1) local interactions play a critical role in the formation of regional and global patterns, while large-scale factors set constraints; (2) the exact behavior of complex systems is inherently unpredictable; (3) the traditional system stability based on homeostatic equilibrium is unachievable; and (4) system metastability (or nonequilibrium resilience) is determined primarily by the system's internal diversity, flexibility, and adaptability in response to unpredictable environmental changes.

Cities and urban landscapes are prototypical examples of self-organizing complex systems that have a large number of diverse components interacting nonlinearly (Portugali, 2000). It is extremely difficult or impossible to precisely predict the ecological and socioeconomic future of such systems no matter how much information we have on them—a view that completely defies the traditional Newtonian determinism. But this does not mean that we cannot understand or even influence their dynamics. Urban forests are a part of the self-organizing and complex urban landscape, and their structure, function, and interactions with other landscape components will affect the landscape's behavior. As such, planning and design should aim to increase the entire system's ability to cope with environmental uncertainties and extreme events (e.g., floods, fires, and epidemics that are intensified by humans). Equally important is the realization that humans are also an affected component of the complex system, not just a source of disturbance. As the most active, and sometimes most powerful, agents in urban landscapes, we have important roles to play in shaping their dynamics. We cannot precisely predict the urban future, but we can certainly influence it through our actions.

Aggregate-with-Outliers Principle

Forman (1995) proposed a landscape planning principle, the aggregate-with-outliers principle, which states that "one should aggregate land uses, yet maintain corridors and small patches of nature throughout developed areas, as well as outliers of human activity spatially arranged along major boundaries." This principle accommodates several important landscape ecological attributes. In particular, intentional aggregation of large patches of natural vegetation protects aquifers and stream networks, provides habitats for large-home-range species and interior-requiring species, and maintains a more natural disturbance regime and a high degree of landscape connectivity. Landscapes with patches of variable sizes provide habitats for a range of species from specialists to generalists. While vegetated corridors can enhance species movements and landscape connectivity, the overall multiple-scale, heterogeneous planning promotes "risk spreading," genetic variation, and multipurpose socioeconomic activities (Forman, 1995). In addition, Dramstad et al. (1996) illustrated 55 more specific landscape ecology principles for landscape architecture and land-use planning. The preferred characteristics of patches, edges/boundaries, corridors/connectivity, and landscape mosaics are discussed for the purpose of conserving biodiversity, an increasingly important goal from the point of view of urban planners or policy makers (see Dramstad et al., 1996, for specific examples).

Discussion and Conclusion

We are witnessing a moment in human history when, for the first time, the majority of the global human population lives in urban areas. The plethora of environmental and socioeconomic problems that challenge most cities throughout the world suggests that our cities, in general, need to be designed, planned, and managed better so as to become more ecologically and socioeconomically sustainable. Indeed, a new urbanism has been called for, which is based fundamentally on promoting the ecological relevance and limits of urban design and planning (Beatley, 2000). Urban forestry is an important part of this endeavor. Urban trees and forests often form a hierarchy of patches from isolated individuals to networks of corridors and to relatively large and contiguous patches (which are not always managed by the same municipal or governmental agencies and departments—fragmented patches run by fragmented often undercommunicating agencies). Urban forests may function as an air/water purifier, a temperature modulator or energy saver, a soil stabilizer, a wildlife habitat, a noise barrier, a landscape beautifier, a real estate value booster, and even a psychological comforter! However, despite their large-scale ecological roles, urban forests have traditionally been studied and managed largely at local, rather than regional, scales.

From a landscape ecological perspective, in planning and designing urban forests and eco-cities, we must consider various levels of nested contexts and expand our thinking (1) beyond "trees" to consider their connections and interactions with higher levels of vegetation aggregates, such as forest patches, corridors, and networks; (2) beyond "forests" to consider how forest patches interact with other land-use/cover types in space and time within urban areas; (3) beyond "urban" to take into account the regional environmental context of the city and its influence on forested habitats; (4) beyond "science" (in the classic and narrow sense) to develop an interdisciplinary landscape ecology of cities that integrates science with planning, designing, and management practices; (5) beyond "now" to plan for long-term environmental and socioeconomic sustainability; and (6) beyond framing our thinking in terms of "homeostatic stability" so we can build "cities of resilience" that are capable of coping with surprises generated by the nonlinear interactions originating from inside and unpredictable environmental changes from outside the city.

To achieve these goals, I have argued that urban forests need to be viewed as an integral part of the urban landscape—a dynamic patch mosaic system. As such, a landscape ecological perspective is needed for urban forestry. Specifically, several principles can be used to guide the practice of urban forestry and planning, including hierarchy theory of landscapes, the pattern-process principle, landscape connectivity, metapopulation theory, landscape self-organizing complexity, and the aggregate-with-outliers principle. Of course, landscape ecology is only one of a number of ecological, environmental, and social sciences that are relevant to urban forestry and the realization of eco-cities. But I argue that the perspectives provided by landscape ecology provide a spatially explicit, interdisciplinary framework through which pattern and process within and across cityscapes can be related. They also facilitate the communications among scientists, practitioners, policy makers, and the public because concepts of pattern and process, connectivity and functionality, and hierarchical components and linkages are essential for both research in and the practice of urban forestry.

Acknowledgments This chapter is based on an invited presentation at the International Symposium on Urban Forestry and Eco-Cities, Shanghai, September 16–22, 2002. I would like to thank Margaret Carreiro and anonymous reviewers for helpful comments on the manuscript of this chapter. My research in urban landscape ecology has been supported by grants from U.S. Environmental Protection Agency (EPA) (Science to Achieve Results Program, R827676-01-0) and U.S. National Science Foundation (NSF) (DEB 97-14833/CAP-LTER and BCS-0508002).

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Author Queries:

[Au1]: Beatley ref: state or country for Covelo?
[Au2]: Pickett et al. (1997) had an extra set of initials. Pls verify that names and initials are correct.
[Au3]: Troll ref: volume?

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