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# Urban Principles for Ecological Landscape Design and Maintenance: Scientific Fundamentals

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## Keywords

urban ecology, concepts, theory, heterogeneity, ecosystem, coupled human-natural systems

## Acknowledgements

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# Urban Principles for Ecological Landscape Design and Management: Scientific Fundamentals

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**Abstract**

Urban ecology is a rapidly developing scientific discipline with great relevance to sustainable city design and management. Though several frameworks have been proposed in the last 10 years, urban ecology, as yet, has no complete, mature theory. There are, however, general principles emerging that may facilitate the development of such a theory. In the meantime, these principles can serve as useful guides for ecological landscape design and maintenance. This paper aims to use the principles to conceptually frame a series of papers to follow in this special issue. The main ecological principles concerning cities are that: 1) Cities are ecosystems; 2) Cities are spatially heterogeneous; 3) Cities are dynamic; 4) Human and natural processes interact in cities; and 5) Ecological processes are still at work and are important in cities. The first three principles address the structure of cities and the change in structure through time. The remaining two principles focus on ecological processes in cities. We briefly summarize each of these principles and their roots in the ecological and design fields. Each principle points to ecological functions that can be translated into ecosystem services. Application of these principles to ecological landscape design and maintenance is discussed.

**Keywords**

Urban ecology; concepts; theory; heterogeneity; ecosystem; coupled human-natural system; landscape design; management.



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## INTRODUCTION

Though urban ecological research reaches back to the early 20th century, it has only recently emerged into the ecological mainstream (Collins et al. 2000). An urban ecology theory has not been articulated, and consequently, much of the accumulated wisdom of the science, and its framework for advance and application, are not widely appreciated. Yet there exist individual principles and emerging generalizations about the structure and function of urban ecosystems (Alberti 2008). Individually, the principles have been put forth in a variety of contexts, and quantitative data are increasingly provided to support them (Cadenasso et al. 2006b). Here we bring these principles together to provide a structure that increases the value of the individual ideas and to make the body of insight more useful for practitioners. Because the ecological science of urban systems is still developing, the principles presented here will undoubtedly be refined, expanded, or perhaps even replaced as the field evolves. However, it is important for the development of an integrated, ecologically-based science of urban systems that this theoretical milestone be marked and summarized.

An additional goal of this paper is to link the emerging theory of urban ecology to the ongoing dialog about ecological design and management of landscapes (Johnson and Hill 2001; Nassauer 2001; Spirn 2001; McGrath et al. 2007). Already there is much good advice and practice on ecologically motivated site design and landscape architecture (Dramstad et al. 1996; Ndubisi 1997; Steiner 2002). One leading example is the Sustainable Sites Initiative (2007). This and other efforts are aimed at enhancing the ecosystem services and reducing the ecological degradation associated with the design and management of landscapes in urban areas. The ecosystem services recognized by the Sustainable Sites Initiative owe much to the Millennium Ecosystem Assessment (2003). Hence, there are already shared roots between the science and the practice. Our intent here is to clarify the scientific basis of 5 urban principles. These principles point to ecosystem functions that translate to services in urban landscapes. We present the scientific principles first, and then discuss implications for ecological landscape management and design in the final section of the paper.

The five principles are that 1) cities or urban areas are ecosystems, 2) they are heterogeneous, 3) they are dynamic, 4) their human and biophysical components interact, and 5) biophysical processes remain important in them. The first principle, that urban areas are ecosystems, lays out the fundamental assumption of contemporary urban ecology. We define the concept of ecosystem as it is traditionally used in ecological science, and indicate what must be added to explicitly address urban systems. The urban ecosystem concept is inclusive of the most intense levels of urbanization, but it also addresses the structure and function of the exurban fringe. The remaining principles draw out more specific implications of the overarching principle that cities are ecosystems. There are many connections between the individual principles and a comprehensive perspective on management and design of urban landscapes emerges from considering all the principles together. The second principle recognizes that urban systems are spatially heterogeneous. Spatial relationships are thus key to understanding, designing, and managing the individual patches of urban systems, as well as the whole urban matrix. The third principle, that urban systems are dynamic, emphasizes that the spatial heterogeneity and the ecological and social processes that connect patches are not stationary through time. The fourth principle, that human and biophysical components of urban systems interact, emphasizes one of the key aspects of the ecosystem concept as it applies to urban areas. Finally, the fifth principle, that biophysical processes remain important in urban systems, emphasizes that even when ecological processes are obscured by built and social processes and structures, they can be capitalized on for landscape design and management. Together, these five principles have implications for how urban landscape projects and management of different urban landscape patches are conceived, constructed, linked, and managed.

Before presenting the principles, it is necessary to define what we mean by a principle. Theories are the conceptual tools by which sciences are structured and advanced (Pickett et al. 2007). They contain a wide array of interacting components. A complete theory consists of 10 components plus the statement of domain (Table 1). Some of these are primarily conceptual, others combine conceptual and empirical information, and some are largely empirical. In other words, theories are combined conceptual and empirical constructs. The components that are entirely or partially conceptual can be considered to be principles, as opposed to the factual or primarily empirical observations. One kind of conceptual tool in theory that we exclude from the category of principle is models. While models are conceptual, they combine multiple concepts, definitions, and relationships, and hence are complex constructions that bring principles together as an explanatory or predictive tool. A review of urban ecological models is beyond our scope. Rather, we present an overview of the current state of the major principles of urban ecology. Our list of principles is not exhaustive, but focuses on those which are most relevant to ecological landscape design and management.

**Table 1.** Components of theory and their definitions. All components are developed within a stated domain for the theory. A theory increases in completeness as more of the components are addressed. The components are not necessarily sequential in development (Adapted from Pickett et al. 2007).

Theory completeness

DOMAIN*

| COMPONENTS | DESCRIPTION |
|---|---|
| Assumptions | Conditions or structures needed to build the theory |
| Concepts | Labeled regularities in the phenomena |
| Definitions | Conventions and prescriptions necessary for the theory to work with clarity |
| Facts | Confirmable records for phenomena |
| Confirmed generalizations | Condensations and abstractions from a body of facts that have been tested or systematically observed |
| Laws | Conditional statements of relationship or causation, statements of identity, or statements of process that hold within a universe of discourse |
| Models | Conceptual constructs that represent or simplify the structure and interaction sin the material world |
| Translation modes | Procedures and concepts needed to move from the abstractions of a theory to the specifics of application or test or vice versa |
| Hypotheses | Testable statements derived from or representing various components of theory |
| Framework | Nested causal or logical structure of a theory |

*Domain refers to the scope in space, time, and phenomena addressed by a theory; specification of the universe of discourse for a theory.

**Cities are Ecosystems**

The first major principle posits that urban areas, which we call "cities" for short, are ecosystems. This may be surprising if ecosystems are considered to be strictly self-maintaining, homeostatic, and essentially closed entities. However, the core ecosystem definition does not, in fact, invoke these assumptions. Simply put, an ecosystem is the interaction between a biotic complex and a physical complex within an area bounded for research purposes (Figure 1). This is the essence of Tansley's (1935) original definition of the ecosystem, and it is the core that has survived to motivate contemporary research and application (Jax et al. 1998; Pickett and Cadenasso 2002; Jax 2006). Whether a particular ecosystem is closed, homeostatic, or autotrophic, are empirical questions to be answered through research, not a presupposition of the basic concept.

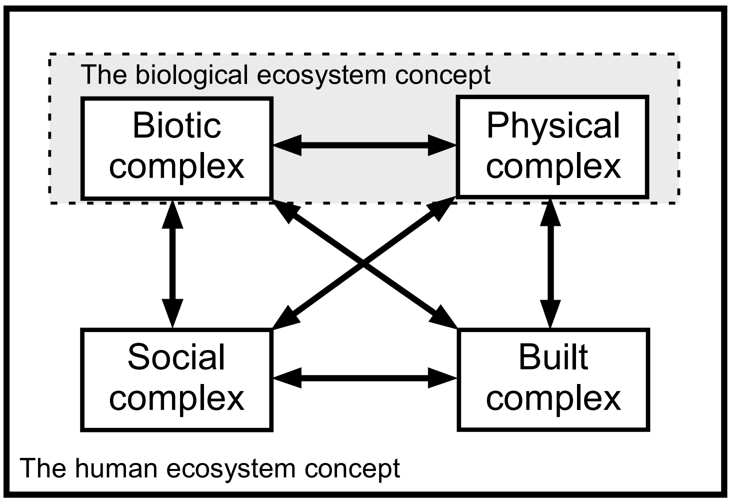


**Figure 1.** The biological and human ecosystem concepts compared. The biological concept includes biotic and physical complexes, while the human ecosystem concept explicitly adds social and built complexes. While buildings, infrastructure and land modifications are certainly physical entities, we use "built" here to explicitly address these anthropogenic components of the system. All the complexes are components of urban ecosystems, spanning cities, suburbs, and exurbs.

Cities are ecosystems by virtue of having interacting biological and physical complexes. There are organisms in cities, including people, as well as air, soil, water, light, and physical regulators such as temperature and day length. Of course, the biotic complex in cities has complex social structure (Grove et al. 2005, 2006a,b) including institutions (Steiner 2002). People are spatially and temporally organized into such institutions as households, neighborhoods and communities, different kinds of associations, as well as agencies, congregations, businesses, and markets. Social structure results from population density, age structure, ethnic and racial composition, economic class, and lifestyle. This richness of social structures and interactions are the core of an inclusive conception labeled the human ecosystem framework (Machlis et al. 1997). Likewise, the physical complex of cities contains not only the native substrates and soils, and any remaining or newly emergent non-managed vegetation and animal populations, but also highly modified or covered soils, maintained and introduced vegetation, buildings, roads, utility infrastructure, and various kinds of paved surfaces. Thus, an urban ecosystem has some additional complexities compared to wild or agricultural ecosystems (Cadenasso et al. 2006a). However, the exact nature of the new structures that contribute to both the physical and the biotic complexes in cities can be seen as extensions of the basic ecosystem concept (Tansley 1935), and not violations of its definition (Figure 1; Grimm et al. 2003). Because urban ecosystems include novel human artifacts such as buildings, infrastructure, and modified land forms, we emphasize this additional layer of complexity as the built component. Cities, in short, are human ecosystems, with biotic, social, physical, and built components all interacting with each other (Machlis et al. 1997; Pickett et al. 1997; Grimm et al. 2000; Alberti et al. 2003).

The ecosystem concept does not presuppose a single spatial scale. Instead, the boundaries of the system are defined by the research question (Likens 1992) so that ecosystems can be of any size. This affords the concept great flexibility because the entire city can be considered an ecosystem, but so too can a watershed, neighborhood and even an individual parcel within the city. In other words, any spatial arena that contains interacting physical and biotic complexes can be an ecosystem. Smaller ecosystems are physically nested within larger ecosystems. Such hierarchical thinking is key to applying ecological insights to landscape design (Steiner 2002).

Because of the inclusiveness of the concept, the components must be specified by the user, and the particular research question addressed at each scale may differ. A scale particularly relevant to ecological landscaping is the parcel scale, which refers to a single management unit or household property. At this scale, occupants or managers of each parcel determine the types, amount, and arrangement of materials on the land such as vegetation, impervious surfaces, and buildings. In addition, management decisions affect 1) the amount of water coming into and going out of the parcel, 2) fertilizer use and potential runoff of nutrients and pollutants from the property, and 3) the amount of energy used to maintain the physical and biotic components.

**Cities are Heterogeneous**

When viewed from a distance, or represented at coarse, regional scales, urban areas are often depicted as rough edged, amoeboid splotches on a contrasting, often green, background (Batty 1996). While understanding the regional and global distribution of urban areas is important because it points out their current extent and tracks their continued spread (Alig et al. 2004), it neglects their internal heterogeneity, which is one of their most salient ecological features. Heterogeneity has been adopted by contemporary ecology as one of its main theoretical and research tenets. Ecologists have discovered a major role for spatial differentiation in natural processes at various scales (Turner 1987, 1989; Kolasa and Pickett 1991; Pickett and Cadenasso 1995; Wiens 2000; Turner and Cardille 2007). So too must urban ecology be concerned with heterogeneity (Pickett et al. 2001; Luck and Wu 2002; Shane 2005; Band et al. 2005; Cadenasso et al. 2007). Heterogeneity in urban landscapes can be caused by both biophysical and social structures and processes. In turn, biophysical and social processes respond to urban spatial heterogeneity. Urban heterogeneity is often relatively fine scaled within cities. Urbanists frequently comment on the stark and sudden changes in urban fabric from block to block or between subdivisions (Clay 1973; Shane 2005). Heterogeneity is reinforced in cities because of the effect of parcelization – the fact that tenancy is based on legally or socially recognized property boundaries. Such parcelization is not only the result of ownership. Heterogeneous structure and management can also appear in patches of public land that have been appropriated or strongly influenced by a person or group. Differentiation of life styles and pressure for social identity within neighborhoods may lead to clear distinctions between patches in cities (Gottdiener and Hutchison 2000; Grove et al. 2006a; Troy et al. 2007). In other words, social processes generate quite fine scale spatial differentiation, which operates through the level of investment in a parcel, the aesthetic preferences of the tenants, and their management habits and methods (Grove and Burch 1997; Dow 2000; Martin et al. 2004; Grove et al. 2006b; Byrne 2007; Gobster et al. 2007; Shane 2007).

Social drivers influence the biophysical heterogeneity of urban systems. This heterogeneity can be expressed by three broad kinds of structural elements that exist and interact in cities (Ridd 1995): buildings and other structures, vegetation, and surfaces. The meaning of buildings and vegetation is intuitive here. The nature of surfaces is more complex, because this category can include human-made surfaces, such as pavement, native surfaces such as soil or rock, and hybrid surfaces, such as soil made bare by construction or other human activities. The three general categories of structural cover can all exist within particular locations. For instance, a city patch may include houses and outbuildings, the paved surfaces of streets, walks, and driveways, and vegetation cover consisting of an overstory of trees and a ground layer of grasses and herbs. Myriad kinds of patches can be discerned based on the relative proportions of these cover types. A new integrated classification system differentiates urban patches based on this logic (see Cadenasso et al. 2007 for further discussion). The fundamental structures of buildings, vegetation, and surfaces, establish the biophysical template upon which additional kinds of social structures and processes can be layered. Social structures include demographics, ethnicity, and education, and social processes include flows of traffic or waste water in different kinds of infrastructural networks, for example. Therefore, social structures and processes act on, and respond to, a biophysical template created by vegetation, buildings, and surfaces. The dynamics and interactions among anthropogenic biophysical components will be explored more fully in the next two principles. The complexity of the different kinds of heterogeneity and their interactions are conspicuous features of urban ecosystems (Cadenasso et al. 2006a).

**Cities are Dynamic**

The spatial heterogeneity outlined above also has a temporal dimension. Change in the structures and flows within cities, and between cities and other ecosystems lend a dynamic element to urban form and morphology (Decker et al. 2000; Kaika 2005; Shane 2005). The built structures, vegetation, and surfaces, as well as the process networks and rates, are subject to change due to many causes (Pickett et al. 2001, 2004; Redman et al. 2004). One cause is vegetation succession. The tendency of larger, slower growing plants to become dominant over time shapes a city's landscape texture. Older neighborhoods and suburban developments can support large trees in both public rights of way and residential yards. The large trees are subject to senescence and mortality over long time scales. Younger neighborhoods may have only small saplings or trees and, thus, less canopy cover. Another major cause of change is disturbance. For example, in older neighborhoods, large mature trees may be susceptible to damage by high winds and ice or snow loading. Thus, the dominant canopy can come and go, often in patches defined by impact of external disturbance events.

The third cause of dynamism in cities is management. In the case of neighborhood tree cover, management by different households may cause the vegetation succession to differ from parcel to parcel, and from neighborhood to neighborhood (Troy et al. 2007). How vegetation is managed in specific areas may depend on peer pressure, aesthetic preferences by different groups or classes, or availability of disposable income to devote to yard care (Hope et al. 2003, 2006; Martin et al. 2004; Grove et al. 2006b). Furthermore, even management in public rights of way or public parks may be differentially influenced over time by the contrasting access to political power or the degree of community organization in different neighborhoods (Troy et al. 2007).

Many of the kinds of dynamics noted above change with aging of households, i.e., whether there are young children present or not, or whether the adult householders are retired and spend much time managing property. They can also change as different groups migrate into and through a city. The sustainability of American cities as social phenomena is due in large part to a steady flow of new migrants from within the country or from beyond national borders. The decisions of developers and the real estate industry to focus on certain areas, and neglect others is also a cause of dynamism in cities. The current foreclosure epidemic is an example of a driver of dynamism in cities, in some cases leading to vacancy, vandalism, and even to demolition of relatively new houses (Johnson 2008).

**Human and Natural Processes Interact**

The principles presented to this point lay out the nature of the structure of cities. The principles have suggested the complexity of urban ecosystem components, the spatial patterning they may have, and the fact that coarse and fine scale dynamics exist within the multiple kinds of patch mosaics found across metropolitan areas. The fourth principle focuses on the interactions among the anthropogenic and the biophysical components.

We will present two examples of human-biophysical interaction. The first is a historical one from Baltimore, Maryland, USA (Boone 2003). In the 1880s, before the installation of a sanitary sewer system, Baltimore's sanitary needs were served by cesspools and privies for individual buildings and properties. However, these facilities were inadequate to properly decompose and filter the waste of the large population. As a consequence, 25% of children died within their first year from waterborne gastrointestinal diseases (Boone 2003). These deaths were concentrated in low lying areas of the city where drainage was poor. Many residents who could move to new suburban enclaves did so, leaving poorer residents and those who were subject to legal and social segregation behind. The continuing high infant mortality rates precipitated a crisis that led to the appointment of a city health officer, and ultimately to the completion of a sanitary sewer system in 1911. As a result, low lying areas of the city became economically and socially valued for their ability to support high residential densities in some places and commercial development in others (Boone 2003). The economic and racial segregation that began before the construction of the sewer system established a spatial pattern that has been reinforced and exacerbated by the century of suburbanization since then. The role of sanitation in shaping the spatial patterns in Baltimore is clear. Similar relationships have been found in other cities (Melosi 2000).

The second example concerns the controls on plant species richness in the Central Arizona-Phoenix region, as elucidated by Hope et al. (2003). General ecological theory, focusing on non-inhabited landscapes, posits that species diversity is related to resource heterogeneity, as controlled by such features as elevation and disturbance. In the urban matrix of Phoenix, current land use and the echo of prior agricultural land use were found to be important determinants of species diversity in addition to elevation. The current social environment also affected the richness of genera in sample areas. Household income and age of housing were dominant correlates of biotic richness in the urban land covers (Hope et al. 2003, 2006).

**Ecological Processes Remain Important in Cities**

Cities have been viewed by many specialists as social and engineering inventions, where ecological processes may be legitimately neglected (Macionis and Perillo 2001). Ecologists for their part have largely ignored cities (Grimm et al. 2008). However, an accumulating body of urban ecological research is making up for this neglect and is concluding that ecological processes are not absent from the urban mosaic. Of course, the capacities of urban green spaces to support biodiversity, mitigate climate extremes, and facilitate infiltration of storm water are by now well recognized urban ecological services (Sukopp et al. 1995).

But the urban landscape, beyond just green spaces, can also provide ecological services. Concepts and approaches basic to ecological research can be applied to urban areas in an effort to understand how the city itself functions as an ecosystem (Alberti et al. 2003). For example, nitrate, a form of nitrogen which is an important water pollutant, enters aquatic systems from adjacent lands (Cadenasso et al. 2008). A budget was calculated for the inputs and outputs of nitrogen in the Gwynns Falls watershed in metropolitan Baltimore. Nitrogen inputs included regional estimates of loading from the atmosphere (11.2 kg N/ha/yr) and from home lawn fertilization (14.4 kg N/ha/yr). Outputs were measured as stream N flux over three years in stream reaches draining forest, suburbs, and agricultural areas in the Gwynns Falls watershed. The forested watershed had, as expected, the highest nitrogen retention, calculated as 95% of inputs. Nitrogen retention in the suburban and agricultural watersheds were surprisingly high at greater than 75%, indicating that substantial biotic retention occurred in those modified portions of the landscape as well. Groffman et al. (2004) attribute the unexpectedly high retention in suburban areas to the vegetated and pervious components of these landscapes. This result illustrates the capacity of urban systems to perform ecological services; additional examples include carbon sequestration and storm water retention (Pickett et al. 2008).

## APPLICATION TO ECOLOGICAL LANDSCAPE DESIGN AND MANAGEMENT

The five principles outlined above suggest an integrated conceptual structure for ecological understanding of urban ecosystems. In addition, they also indicate perspectives and approaches to landscape design and practice that can improve the ecological resilience and function of urban systems (Table 2). The principles, and the emerging theory they suggest, affirm the value and validity of practical recommendations made by the Sustainable Sites Initiative (http://sustainablesites.org/index.html) and by pioneering landscape architects (McHarg 1969, 1997; Lyle 1999; Spirn 1984; Steiner 2002; Thompson and Steiner 1997). The value is not in the individual principles, but in the integrated, dynamic ecological view of systems comprising interacting cities, suburbs, and exurbs. The principles point to functions that provide ecological services of value in urban ecosystems (Millennium Ecosystem Assessment 2003).

**Table 2.** A brief summary of the general implications of each of the five principles of urban ecology for ecologically motivated landscape design and management. This summary provides theoretical motivation for existing and emerging best design and management practices in landscape architecture.

| Principle | Summary of Implication for Landscape Design |
|---|---|
| Cities are ecosystems | Design affects all four components of human ecosystems (Fig. 1) |
| Cities are heterogeneous | Design should enhance heterogeneity, and its ecological functions |
| Cities are dynamic | Design must accommodate internal and external changes projects can experience |
| Human and natural processes interact in cities | Design should recognize and plan for feedbacks between social and natural processes |
| Ecological processes remain important in cities | Remnant ecological processes yielding ecological services should be maintained or restored |

The first principle, that cities are ecosystems, suggests that landscape design theory and management practice must address all the components of such systems. Urban ecosystems include four broad kinds of components – organisms, a physical setting and conditions, social structures, and the built environment – all interacting with one another (Figure 1). The interactions take the form of flows of information, matter, energy, and organisms. Landscape designs and management strategies that are aimed at one or two of these components or interactions, in reality have the potential to affect them all. Landscape designs that acknowledge and work with the connections between the social, biological, physical, and built components of the system are much less likely to produce unintended negative consequences, and are more likely to contribute to ecological sustainability. Furthermore, enhanced quality of urban life depends on all components of the urban ecosystem, not just some of them.

The second principle, that urban systems are spatially heterogeneous, suggests that interactions and transfers among patches within the urban matrix are affected by landscape design and management. Urban landscape design should carefully consider the heterogeneity and its role in maintaining desirable functions such as biodiversity, storm water retention, microclimate mitigation, and carbon sequestration. The interaction between a particular landscape project and adjacent patches of similar or contrasting landscape structure can enhance the function and value of individual projects. This may mean paying particular attention to the boundaries between contrasts within or between projects to enhance or protect from exchanges (Cadenasso and Pickett 2007). Heterogeneity is one of the keys to the resilience of natural ecosystems. The question of how to adapt this insight to cities, suburbs, and exurbs, suggests an opportunity for creative landscape design and management.

The third principle, that cities are dynamic, means that landscape designs should accommodate change (Plunz 2007). Natural disturbances, extreme climate events, shifting economic investment or disinvestment, the maturation of households, and the aging of or renovation of infrastructure are but some of the examples of the kinds of dynamism that landscape designs and management will have to respond to. Persistent equilibrium in cities is unlikely (Pulliam and Johnson 2001). Designs that plan for successional changes in vegetation, have redundancies in the face of disturbance, or that encourage use by different age groups may be more resilient in changing cities. In addition, planning for landscapes that can deal with climate change (Carreiro and Tripler 2005; Grimm et al. 2008) is an opportunity to adapt to an ongoing global dynamic of monumental proportions.

The fourth principle, that human and natural processes interact in urban ecosystems, suggests that both of these major categories must be addressed as landscape design goals. A design that satisfies only obvious social criteria, such as recreation or efficiency of commerce, misses an opportunity to contribute to ecosystem services that may ultimately have great social value. All landscape designs and management schemes should be judged for their ability to contribute to both social and ecological goods and services, and to reduce both social and ecological risks and vulnerabilities (Steiner 2002; Grove et al. 2007).

The fifth principle, that ecological processes are present in cities, means that landscape designs and management practices have the opportunity to preserve and promote those basic biological processes upon which human health and well being depend (e.g., Sustainable Sites Initiative 2007). It will be important to provide for these functions even in areas beyond the large green parcels usually targeted for this kind of benefit. The control of water flow and infiltration (Shuster et al., Carter and Butler, this volume), the retention of limiting and hence potentially polluting nutrients (Baker et al., this volume), the sequestration of carbon dioxide, the neutralization of toxics, the maintenance of soil respiration, the production of biomass, the amelioration of climate extremes, the mitigation of natural disturbance, and the preservation of biodiversity (Marzluff and Rodewald, this volume), are but some of the processes that can exist in various places in designed systems (Palmer et al. 2004). Landscape designs and management protocols can be purposefully planned so as to maintain, or in some cases restore, as many of these kinds of natural processes as possible throughout the urban matrix. As such, landscape design and management can provide creative new ways to insinuate ecological processes in cities (Felson and Pickett 2005).

As the ecological theory for urban systems matures, additional principles may be added, and the existing principles may be refined or expanded. However, these five principles together form a broad foundation for a successful theory of urban ecosystems, and together they lend support to the practical suggestions already articulated for the management and design of landscapes in urban ecosystems (Dramstad et al. 1996; Nassauer 2001; Steiner 2002). Perhaps promulgation of these principles will encourage additional application of the ecological strategies already explored and pioneered (e.g., Ahern 1991) by landscape architects and other urban designers and managers.



 

All of the principles and applications above act in an environment conditioned on the feedback between human actions and perceptions and ecological structures and functions (Plunz 2007; Pickett and Cadenasso 2008). There are many unanswered questions about the relationships between ecological principles and urban landscape design and management. How can landscape design and management be used to educate people about ecological processes in cities and the role of hidden nature in the city? How can landscapes mediate the human perceptions and actions that will affect the other components of the system? How can landscape design and maintenance focus and transmit ecosystem services? How can ecologically motivated landscape design be an instrument of just allocation of environmental benefits and risks? Ecological-informed landscape design and management has the potential to translate the fundamental ecological principles that are emerging from the field of urban ecology into practice. It also has great potential to bring the structure and function of cities much closer to the ideals of sustainability embodied in the structure and function of native ecosystems. Even though the ecological principles articulated here are preliminary, they can offer important support for ecological landscape theory and practice. These principles resonate throughout the other contributions included in this special issue.

**ACKNOWLEDGEMENTS**

We thank Dr. Loren Byrne for his leadership in the “Ecological Landscaping” conference held in October 2007 and for providing us this opportunity to articulate our ideas. Our work has benefited greatly from interactions with generous colleagues in the Baltimore Ecosystem Study. We gratefully acknowledge support from the US National Science Foundation (NSF), Long-Term Ecological Research the program (DEB-0423476) and the NSF Biocomplexity in Coupled Natural-Human Systems program (BCS-0508054). The USDA Forest Service contributes substantially to research in Baltimore from which we draw here. The manuscript was greatly improved by comments from two anonymous reviewers.

**LITERATURE CITED**

Ahern J. 1991. Planning for an extensive open space system: linking landscape structure and function. Landscape and Urban Planning 21: 131-145.

Alberti, M., J. M. Marzluff, E. Shulenberger, G. Bradley, C. Ryan, and C. Zumbrunnen. 2003. Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. BioScience 53:1169-1179.

Alberti, M. 2008. Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems. Springer, New York. 366 pp.

Alig, R. J., J.D. Kline, and M. Lichtenstein. 2004. Urbanization on the US landscape: looking ahead in the 21st century. Landscape and Urban Planning 69:219-234.

Batty, M. 1996. Visualizing urban dynamics, pp 297-320. In Longley P. and M. Batty (Eds.). Spatial Analysis: Modeling in a GIS Environment. Wiley and Sons, New York.

Band, L. E., M. L. Cadenasso, C. S. B. Grimmond, J. M. Grove, and S. T. A. Pickett. 2005. Heterogeneity in urban ecosystems: patterns and process, pp 257-278. In Lovett, G., C. G. Jones, M. G. Turner, and K. C. Weathers (Eds.). Ecosystem Function in Heterogeneous Landscapes. Springer-Verlag, New York.

Boone, C. G. 2003. Obstacles to infrastructure provision: the struggle to build comprehensive sewer works in Baltimore. Historical Geography 31:151-168.

Byrne, L.B. 2007. Habitat structure: A fundamental concept and framework for urban soil ecology. Urban Ecosystems 10:255-274.

Cadenasso, M.L., S.T.A. Pickett, L.E. Band, G.S. Brush, M.F. Galvin, P.M. Groffman, J.M. Grove, G. Hagar, V. Marshall, B. McGrath, J. O'Neil-Dunne, B. Stack, and A. Troy. 2008. Exchanges across land-water-scape boundaries in urban systems: Strategies for reducing nitrate pollution. Annals of the New York Academy of Sciences. 1134:213-232.

Cadenasso, M.L., S.T.A. Pickett, and J.M. Grove. 2006a. Dimensions of ecosystem complexity: heterogeneity, connectivity, and history. Ecological Complexity 3:1-12.

------. 2006b. Integrative approaches to investigating human-natural systems: the Baltimore Ecosystem Study. Natures, Sciences, Sociétés 14: 1-14.

Cadenasso, M.L., and S.T.A. Pickett. 2007. Boundaries as structural and functional entities in landscapes: understanding flows in ecology and urban design, pp. 116-131. In McGrath, B., V. Marshall, M.L. Cadenasso, J.M. Grove, S.T.A. Pickett, R. Plunz, and J. Towers. (Eds.). Designing Patch Dynamics. Columbia, Graduate School of Architecture, Planning and Preservation, New York, NY.

Cadenasso, M.L., S.T.A. Pickett, and K. Schwarz. 2007. Spatial heterogeneity in urban ecosystems: reconceptualizing land cover and a framework for classification. Frontiers in Ecology and Environment 5:80-88.

Carreiro, M.M. and C.E.Tripler 2005. Forest remnants along urban-rural gradients: examining their potential for global change research. Ecosystems 8:568-582.

Clay, G. 1973. Close Up: How to Read the American City. Praeger Publishers, New York. 192 pp.

Collins, J.P., A. Kinzig, N.B. Grimm, W.F. Fagan, D.Hope, J.Wu, and E.T. Borer. 2000. A new urban ecology. American Scientist 88: 416-425.

Decker, E.H., S. Elliott, F.A. Smith, D.R. Blake, and F.S. Rowland. 2000. Energy and material flow through the urban ecosystem. Annual Review of Energy and the Environment 25:685-740.

Dow, K. 2000. Social dimensions of gradients in urban ecosystems. Urban Ecosystems 4:255-275.

Dramstad, W.E., J.D. Olson, and R.T.T. Forman 1996. Landscape Ecology Principles in Landscape Architecture and Planning. Island Press, Covelo, CA. 80pp.

Felson, A.J. and S.T.A. Pickett 2005. Designed experiments: new approaches to studying urban ecosystems. Frontiers in Ecology and Environment 3:549-556.

Gobster, P.H., J.I. Nassauer, T.C. Daniel, and G. Fry. 2007. The shared landscape: What does aesthetics have to do with ecology? Landscape Ecology 22: 959-972.

Gottdiener, M. and R. Hutchison. 2000. The New Urban Sociology. Second Edition. McGraw Hill, New York. 390 pp.

Grimm, N.B., J.M. Grove, S.T.A. Pickett, and C.L. Redman. 2000. Integrated approaches to long-term studies of urban ecological systems. BioScience 50:571-584.

Grimm, N.B., L.J. Baker, and D. Hope. 2003. An ecosystem approach to understanding cities: familiar foundations and uncharted frontiers, pp 95-114. In Berkowitz, A.R., C.H. Nilon, and K.S. Holweg (Eds). Understanding Urban Ecosystems: A New Frontier for Science and Education. Springer-Verlag, New York.

Grimm, N.B., S.B. Faeth, N.E. Golubiewski, C.L. Redman, J. Wu, X. Bei, and J.M. Briggs. 2008. Global change and the ecology of cities. Science 319:756-760.

Groffman, P.M., N.L. Law, K.T. Belt, L.E. Band, and G.T. Fisher. 2004. Nitrogen fluxes and retention in urban watershed ecosystems. Ecosystems 7:393-403.

Grove, J.M., and W.R. Burch, Jr. 1997. A social ecology approach and applications of urban ecosystem and landscape analyses: a case study of Baltimore, Maryland. Urban Ecosystems 1:259-275.

Grove, J.M., W.R. Burch, Jr., and S.T.A. Pickett. 2005. Social mosaics and urban community forestry in Baltimore, Maryland, pp 249-273. In Lee, R.G. and D.R. Field (Eds.). Communities and Forests: Where People Meet the Land. Oregon State University Press, Corvallis.

Grove, J.M., A.R. Troy, J.P.M. O'Neill-Dunne, W.R. Burch, Jr., M.L. Cadenasso, and S.T.A. Pickett. 2006a. Characterization of households and its implications for the vegetation of urban ecosystems. Ecosystems 9:578-597.

Grove, J.M., M.L. Cadenasso, W.R. Burch, Jr., S.T.A. Pickett, K. Schwarz, J.P.M. O'Neill-Dunne, M. A. Wilson, A. Troy, and C.G. Boone. 2006b. Data and methods comparing social structure and vegetation structure of urban neighborhoods in Baltimore, Maryland. Society & Natural Resources 19:117-136.

Grove, J. M., W.R. Burch, M. Wilson, and A.W. Vemuri. 2007. The mutual dependence of social meanings, social capital, and the design of urban green infrastructure, pp 66-77. In McGrath, B., V. Marshall, M.L. Cadenasso, J.M. Grove, S.T.A. Pickett, R. Plunz, and J. Towers (Eds.). Designing Patch Dynamics. Columbia, Graduate School of Architecture, Planning, and Preservation, New York, NY.

Hope, D., C. Gries, D. Casagrande, N.B. Grimm, C. Redman, and C. Martin. 2006. Drivers of spatial variations in plant diversity across the Central Arizona-Phoenix Ecosystem. Society & Natural Resources 19:101-116.

Hope, D., C. Gries, W. Zhu, W. Fagan, C.L. Redman, N.B. Grimm, A.L. Nelson, C. Martin, and A. Kinzig. 2003. Socioeconomics drive urban plant diversity. Proceedings of the National Academy of Sciences 100:8788-8792.

Jax, K., C. Jones, and S.T.A. Pickett. 1998. The self-identity of ecological units. Oikos 82:253-264.

Jax, K. 2006. Ecological units: definitions and application. Quarterly Review of Biology 81:237-258.

Johnson B.R. and K. Hill (Eds.). 2001. Ecology and Design: Frameworks for Learning. Island Press, Washington, DC. 530 pp.

Johnson, P. 2008. Vacant houses spread blight in suburb and city alike. Christian Science Monitor. July 1, 2008. (http://www.csmonitor.com/2008/0702/p01s01-usgn.html?page=1)

Kaika, M. 2005. City of Flows: Modernity, Nature, and the City. Routledge, New York. 200 pp.

Kolasa, J., and S.T.A. Pickett (Eds.). 1991. Ecological Heterogeneity. Springer-Verlag, New York. 332pp.

Likens, G.E. 1992. The Ecosystem Approach: Its Use and Abuse. Ecology Institute, Oldendorf/Luhe, Germany. 166 pp.

Luck, M. and J. Wu. 2002. A gradient analysis of urban landscape pattern: a case study from the Phoenix metropolitan region, Arizona, USA. Landscape Ecology 17: 327-339.

Lyle, J.T. 1999. Design for Human Ecosystems: Landscape, Land Use, and Natural Resources. Island Press, Washington, DC. 279 pp.

Machlis, G.E., J.E. Force, and W.R. Burch. 1997. The human ecosystem. 1. The human ecosystem as an organizing concept in ecosystem management. Society & Natural Resources 10:347-367.

Macionis, J.J., and V.N. Parrillo. 2001. Cities and Urban Life. Prentice Hall, Upper Saddle River, NJ. 474 pp.

Martin, C., P.S. Warren, and A. Kinzig. 2004. Neighborhood socioeconomic status is a useful predictor of perennial landscape vegetation in residential neighborhoods and embedded small parks of Phoenix, AZ. Landscape and Urban Planning 69:355-368.

McGrath, B.P., V. Marshall, M.L. Cadenasso, J.M. Grove, S.T.A. Pickett, R. Plunz, and J. Towers, (Eds.). 2007. Designing Patch Dynamics. Columbia Graduate School of Architecture, Planning and Preservation. New York, NY. 160 pp.

McHarg, I.L. 1969. Design with Nature. Doubleday/Natural History Press, Garden City, NJ. 197 pp.

McHarg, I.L. 1997. Ecology and design, pp. 321-332. In Thompson G.F. and F.R. Steiner (Eds.). Ecological Design and Planning. John Wiley and Sons, New York.

Melosi, M.V. 2000. The Sanitary City: Urban Infrastructure in America from Colonial Times to the Present. Johns Hopkins University Press, Baltimore. 600 pp.

Millennium Ecosystem Assessment. 2003. Ecosystems and Human Well-Being: A Framework for Assessment. Island Press, Washington DC. 137 pp.

Nassauer, J.I. 2001. Ecological science and landscape design: a necessary relationship in changing landscapes, pp. 217-230. In Johnson B.R. and K. Hill (Eds.). Ecological Design: Frameworks for Learning. Island Press, Washington,DC,.

Ndubisi, F. 1997. Landscape ecological planning, pp. 9-44. In Thompson G.F. and F.R. Steiner (Eds.). Ecological Design and Planning. John Wiley and Sons, New York,.

Palmer, M., E. Bernhardt, E. Chornesky, S. Collins, A. Dobson, C. Duke, B. Gold, R. Jacobson, S. Kingsland, R. Kranz, M. Mappin, M.L. Martinez, F. Micheli, J. Morse, M. Pace, M. Pascual, S. Palumbi, O.J. Reichman, A. Simons, A. Townsend and M. Turner. 2004. Ecology for a Crowded Planet. Science 304:1251-1252.

Pickett, S.T.A. and M.L. Cadenasso. 1995. Landscape ecology: spatial heterogeneity in ecological systems. Science 269:331-334.

------. 2002. Ecosystem as a multidimensional concept: meaning, model and metaphor. Ecosystems 5:1-10.

Pickett, S.T.A., W. Burch, Jr., S. Dalton, T.W. Foresman, and R. Rowntree. 1997. A conceptual framework for the study of human ecosystems in urban areas. Urban Ecosystems 1:185-199.

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilon, R.V. Pouyat, W.C. Zipperer, and R. Costanza. 2001. Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. Annual Review of Ecology and Systematics 32:127-157.

Pickett, S.T.A., M.L. Cadenasso, and J.M. Grove. 2004. Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. Landscape and Urban Planning 69:369-384.

Pickett, S.T.A., J. Kolasa, and C. Jones. 2007. Ecological Understanding: The Nature of Theory and the theory of Nature. Second Edition. Academic Press, Boston. 248 pp.

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, P.M. Groffman, L.E. Band, C.G. Boone, W.R. Burch, C.S.B. Grimmond, J. Hom, J.C. Jenkins, N. Law, C.H. Nilon, R.V. Pouyat, K. Szlavecz, P.S. Warren, and M.A. Wilson. 2008. Beyond urban legends: emerging framework of urban ecology, as illustrated by the Baltimore Ecosystem Study. BioScience 58:141-152.

Pickett, S.T.A. and M.L. Cadenasso. 2008. Linking ecological and built components of urban mosaics: An open cycle of ecological design. Journal of Ecology 96: 8-12.

Plunz, R. 2007. Apropos "patch dynamics": notes on indeterminacy as operational philosophy in design, pp 42-53. In McGrath, B., V. Marshall, M.L. Cadenasso, J.M. Grove, S.T.A. Pickett, R. Plunz, and J. Towers (Eds.). Designing Patch Dynamics. Columbia Graduate School of Architecture, Planning and Preservation, New York, NY.

Pulliam, H.R. and B.R. Johnson. 2001. Ecology's new paradigm: what does it offer designers and planners? pp. 51-84. In Johnson B.R. and K. Hill (Eds.). Ecology and Design: Frameworks for Learning. Island Press, Washington, DC.

Redman, C., J.M. Grove, and L. Kuby. 2004. Integrating social science into the Long-Term Ecological Research (LTER) Network: social dimensions of ecological change and ecological dimensions of social change. Ecosystems 7:161-171.

Ridd, M.K. 1995. Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. International Journal of Remote Sensing 16:2165-2185.

Shane, D.G. 2005. Recombinant Urbanism: Conceptual Modeling in Architecture, Urban Design, and City Theory. John Wiley & Sons, Hoboken. 344 pp.

Shane, D.G. 2007. Urban patches: granulation, patterns and patchworks, pp. 94-103. In McGrath, B., V. Marshall, M.L. Cadenasso, J.M. Grove, S.T.A. Pickett, R. Plunz, and J. Towers. (Eds.). Designing Patch Dynamics. Columbia, Graduate School of Architecture, Planning, and Preservation, New York, NY.

Spirn, A.W. 1984. The Granite Garden: Urban Nature and Human Design. Basic Books, New York. 334 pp.

Spirn, A.W. 2001. The authority of nature: conflict, confusion, and renewal in design, planning, and ecology, pp. 29-49. In Johnson B.R. and K. Hill (Eds.). Ecology and Design: Frameworks for Learning. Island Press, Washington, DC.

Steiner, F.R. 2002. Human Ecology: Following Nature's Lead. Island Press, Washington, DC. 237 pp.

Sukopp, H., M. Numata, and A. Huber. 1995. Urban Ecology as the Basis of Urban Planning. SPB Academic Publishing, The Hague. 218 pp.

Sustainable Sites Initiative. 2007. www.sustainablesites.org (accessed 07/10/2008).

Tansley, A.G. 1935. The use and abuse of vegetational concepts and terms. Ecology 16:284-307.

Thompson, G.F. and F.R. Steiner 1997. Ecological Design and Planning. John Wiley and Sons, New York. 348 pp.

Troy, A.R., J.M. Grove, J.P.M. O'Neil-Dunne, S.T.A. Pickett, and M.L. Cadenasso. 2007. Predicting opportunities for greening and patterns of vegetation on private urban lands. Environmental Management 40:394-412.

Turner, M.G. (Ed.). 1987. Landscape Heterogeneity and Disturbance. Springer-Verlag, New York. 239 pp.

Turner, M.G. 1989. Landscape ecology: the effect of pattern on process. Annual Review of Ecology and Systematics 20:171-197.

Turner, M.G., and J.A. Cardille. 2007. Spatial heterogeneity and ecosystem process, pp 62-77. In Wu, J. and R. Hobbs (Eds.). Key topics in landscape ecology. Cambridge University Press, New York.

Wiens, J.A. 2000. Ecological heterogeneity: an ontogeny of concepts and approaches, pp 9-31. In Hutchings, M.J., E.A. John, and A.J.A. Stewart (Eds.). The ecological consequences of environmental heterogeneity. Blackwell, Malden, MA.

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