Chapter 10

URBAN ECOLOGY: A SYNTHESIS

When we speak of Nature it is wrong to forget that we are ourselves a part of Nature. We ought to view ourselves with the same curiosity and openness with which we study a tree, the sky or a thought, because we too are linked to the entire universe.

— Henri Matisse

10.1 A Hybrid Ecology

Scholars working at the interface between ecology and the social sciences have started to articulate the opportunities and challenges for ecology to fully and productively integrate the complexity and global scale of human activity into ecological research (Liu et al. 2007). The future of Earth's ecosystems is increasingly influenced by human action, particularly the pace and pattern of urbanization. An ecology that does not include humans in its theories and experiments will rapidly evolve into paleoecology.[1] Meanwhile, urban scholars will need to expand their approach to fully appreciate that the ecology of a region and its biophysical processes shape the human habitat and the city just as much as do human action and perceptions. They have yet to write the "natural history of urbanization" that Mumford (1956) called for half a century ago, and for the same reason: "only a small part of the preliminary work has been done" (387). It is critical that we understand how human and ecological systems have coevolved over time to generate the present urban world, if we are to anticipate how environmental change will shape the cities of the future.

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[1] Paleoecology studies the ecosystems of the past based on data from fossil and sub-fossil records. Most paleoecological research studies fossil organisms—their life cycle, their living interactions and their natural environment—over the last two million years (known as the Quaternary period), and more precisely the Holocene epoch (the last 10,000 years), or the last glacial stage of the Pleistocene epoch (from 50,000 to 10,000 years ago). This reference to paleoecology is metaphorical. Paleoecology and evolutionary biology are essential to ecology and to urban ecology. Both must inform the ecology of the present and of the future.

Cities are hybrid phenomena. We cannot understand them fully just by studying their component parts separately. Cities are not simply the combination of human and ecological systems. As Walker et al. (2006) point out, coupled human-ecological systems are a "different thing altogether." In conceptualizing coupled human-ecological systems, Westley et al. (2002) suggest that humans are not embedded in ecological systems; neither are ecosystems embedded in human systems. The study of urban ecosystems entails the study of hybrid systems emerging from interactions between human and ecological systems. Cities are the result of simultaneously occurring human and ecological processes in time and in space and the legacy of the simultaneous processes of the past. As Mumford (1956, 388) reminds us, "whether one looks at the city morphologically or functionally, one cannot understand its development without taking in its relationship to earlier forms of cohabitation that go back to non-human species." Thus urban ecology is the study of the coevolution of human-ecological systems, not the separate studies of the human habitat and of the ecosystems upon which humans depend.

In this book, I have argued that we need a theory of urban ecology, a hybrid between urban theory and ecological theory. Emerging models of urban ecology still cannot effectively take into account the complex interactions between humans and ecology. In Chapter 1 I reviewed several conceptual models that have attempted to integrate human and ecological systems to understand the dynamics of urbanizing regions. Emerging urban ecological studies place a different emphasis on one of several approaches. Referring to the traditional distinction in ecology between population-community and process-functional studies, Grimm et al. (2000) distinguish between an "ecology *in* cities" (that primarily focuses on the study of habitats or organisms within cities) and an "ecology *of* cities" (that studies urban areas from an ecological systems perspective). Others emphasize a complex systems approach (Wu and David 2002, Alberti and Marzluff 2004), seeing urban ecosystems as complex dynamic systems of many interacting agents. Similarly to other ecosystems described by Scheffer et al. (2001), shifts in such systems from one relatively stable state to another can be triggered either by the action of slowly changing variables or by relatively discrete shocks. In urban ecosystems these shifts may be controlled by complex interactions between human and ecological processes (Alberti et al. 2006b). For example, the ecological conditions of an urban stream can change from good to poor as a result of an incremental loss or degradation of riparian vegetation, or by substantially paving the drainage basin to make way for a large development or built infrastructure, or by both of these changes occurring simultaneously. Over the long term, what controls the ability of an urban ecosystem to support both its ecological and human function can be affected by slow-changing variables (i.e., climate change) or discrete shocks (i.e., hurricane Katrina) that can force the system over a threshold.

Scholars of urban ecosystems have made important progress in studying interactions between human and ecological processes in such systems (Grimm et al. 2000, Pickett et al. 2001, Alberti et al. 2003), yet we are just beginning to understand their organization and behavior. While several authors have addressed the relationships between urbanization and ecosystem function (Collins et al. 2000, Grimm et al. 2000, Pickett et al. 2001), few have directly asked how human and ecological patterns emerge from these interactions. Nor have they investigated how these patterns control the distribution of energy, materials, organisms, and information in human-dominated ecosystems at the local and global scales, and how human-dominated ecosystems differ from their nonhuman-dominated counterpart. We lack an understanding of the mechanisms linking emerging urban ecosystem patterns to ecosystem processes and controlling their dynamics.

To achieve such an understanding we need to change the way we pose questions and search for answers. The ecologists and social scientists who have begun to investigate questions at the interface between humans and ecological processes have done so within their own academic disciplines (Redman et al. 2000). Furthermore, these studies have privileged the empirical testing of hypotheses developed within these disciplines over the more challenging task of developing hypotheses that explore the interactions. But if we remain within the traditional disciplinary boundaries, we will not make progress towards a theory of urban ecosystems as coupled human-ecological systems, because no single discipline can provide an integrated perspective without bias. Questions and methods of inquiry specific to our traditional domains yield partial views that reflect different epistemologies and understandings of the world. Simply linking these views is not enough to achieve the level of synthesis required to see the urban ecosystem as a whole.

The challenge for scholars of coupled human-ecological systems is to collaborate in generating new research questions, not simply to integrate the findings of disciplinary studies. We need a theory that builds on multiple world views to develop testable hypotheses about the mechanisms that govern coupled human-natural systems. Such a theory requires that scholars of both urban systems and ecology be willing to challenge the assumptions and world views within their disciplines. But that alone is not enough; we must also engage in this process many other social and natural scientists who study human and natural systems from various perspectives.

More importantly, we need to change the way we train the new generation of scholars, especially ecologists, planners, and economists. In graduate school, we are taught to break problems apart into manageable parts. That works for relatively simple problems, but not for complex ones. We cannot reassemble the knowledge that different experts produce separately and expect to understand complex problems—because each expert sees different things and no one expert can see all the connections that allow us to understand the whole. Trying to reconstruct the whole from a fragmented knowledge is a futile exercise as Peter Senge reminds us in *The Fifth Discipline* (1990, 3) by quoting physicist David Bohm: "it is like trying to reassemble the fragments of a broken mirror to see a true reflection."

10.2 Toward a Theory of Urban Ecology

In ecology, theory consists of heuristics used to construct models that describe the interaction of living systems with their environments (Sarkar 2006). In ecology, we have no unified theory, or even general principles comparable to Schrodinger's standing wave equations in quantum physics that describe matter in physical space. Ecological theory builds on principles developed within multiple sub-fields: population ecology, metapopulation ecology, community ecology, metacommunity ecology, physiological ecology, functional ecology, behavioral ecology, and the ecologies of conservation, ecosystems, landscapes, evolution, and conservation (Roughgarden et al. 1989, Sarkar 2006). Similarly, urban theory builds on concepts and principles from urban economics, sociology, geography, political science, anthropology, and urban planning to explain urban systems and their functioning (Short 2006).

A theory of urban ecology will have to build on a plurality of concepts from multiple disciplines to address questions about the mechanisms that govern the behavior of urban ecosystems. These questions are complex and diverse: How do human populations and other organisms come to be distributed in time and space? How do energy and material fluxes emerge from the interactions between humans and ecological processes? How do human populations and activities interact with ecological processes at the levels of the individual, population, and community to determine system stability (i.e., resilience)? How do human populations, interacting with ecological processes, generate emergent system-level behaviors? How do landscape-scale organizations of structures and processes arise? How are they maintained, and how do they evolve? (Alberti et al. 2003).

The challenge for urban ecology is to articulate the discrepancies between ecological theory and observations in urban ecosystems in a set of testable hypotheses and, by exploring differences and communalities with nonhuman-dominated systems, to gain clearer insights into how ecosystems work. With my colleagues on the urban ecology team at the University of Washington, I suggest that integrating humans into ecosystems would provide important opportunities for advancing ecosystem science (Alberti et al. 2003). We suggest that the study of urbanizing regions can lead to fundamental changes in niche theory; it would be possible to distinguish realized niches from fundamental ones on the basis of human interaction. If we redefine the realized niche as an organism's hypervolume of occurrence in the presence of a gradient of human domination, we would be able to identify and quantify the multiple and diverse ways that humans force the population-level ecological functions that structure communities. Understanding how niche assembly functions in human-dominated ecosystems would allow ecologists to directly test the effects of competitors, predators, diseases, and other biophysical changes induced by humans on community organization (Alberti et al. 2003).

Empirical studies conducted at the two Urban Long-Term Ecological Sites (LTER) in Phoenix, AZ and Baltimore, MD, indicate that urban ecosystems may deviate from conventional expectations based on theoretical models of non-human-dominated systems (Alberti et al. 2003, Kaye et al. 2006). Kaye et al. (2006) indicate that urban biogeochemical cycles might be distinct from nonurban systems as a result of human-controlled energy and element fluxes. Concentrated human populations not only alter nutrient sources by changing atmospheric deposition rates and by importing fertilizer and food, but also influence nutrient fluxes in plants and soils through hydrological changes (Kaye et al. 2006). In urban areas, stormwater detention basins, ditches, gutters, and lawns can also be hotspots for denitrification as nitrates and organic matter accumulate (Kaye et al. 2006).

Similarly, urban ecosystems may diverge from nonhuman-dominated systems in what controls the food web dynamics. Trophic dynamics in urban ecosystems are influenced by complex human social processes and feedback mechanisms (Shochat 2004, Faeth et al. 2005). Urbanization in Phoenix, for example, causes shifts from a bottom-up (resource-based) system typical of the Sonoran Desert to a system driven simultaneously by bottom-up and topdown processes (Faeth et al. 2005). In such an environment, predation becomes increasingly important for some taxa as resources become abundant and predictable (Faeth et al. 2005), although these resources are variable across the urban landscape (Hope et al. 2003). Complex trophic dynamics are not predictable based only on knowledge of species composition.

By integrating the complex human interactions with the food web in our studies of urban ecosystems, we can also shed light on another scientific controversy in ecology—the influence of biological diversity on ecological stability (Alberti et al. 2003). Humans make the food web more complex, but despite the complexity of trophic interactions this may not necessarily increase the stability of the ecological or human systems. By decoupling diversity and stability in human-dominated ecosystems, we can explore the importance of other factors such as species identity, rather than simply species richness, to community stability and ecosystem functioning. Investigating the changing relationship between diversity and stability along a gradient of human domination can also clarify when diversity produces stability, when diversity simply means redundancy, and when diversity leads to instability (e.g., diversity caused by invasive exotics).

Marzluff (2005) has tried to resolve a key puzzle for "island biogeography" in human dominated ecosystems by developing formal hypotheses of the processes governing biological diversity in urbanizing landscapes. Expanding on work by Blair (1996, 2001), Marzluff (2005) suggests that in a human-dominated ecosystem, diversity is an emergent property of extinction and colonization forces, but the actions of invading species take on greater relevance (Olden and Poff 2004). By studying bird communities in the Seattle, WA, metropolitan area, Marzluff (2005) has shown that bird diversity peaks at intermediate levels of human settlement primarily because intermediately disturbed forests are being colonized by early successional native species. His research aims to determine the relative importance of colonization versus extinction to bird communities in Seattle and derive testable hypotheses about how extinction and colonization are affected by urbanization to determine avian diversity in urban habitat islands.

From an evolutionary perspective, humans also influence natural selection by changing the genetic fitness of organisms and reconfiguring the physical environment and biogeochemistry (Pimm et al. 1994,Vitousek et al. 1997, Flannery 2001). By changing speciation and increasing extinction, humans are causing evolutionary change (Palumbi 2001). Environmental change resulting from human action can in turn force human cultural and natural selection and fitness. Marzluff and Angell (2005) go further to propose an additional synergy between human culture and the environment—a coevolution of humans and birds–by providing evidence from studying crows and ravens. Populations evolve as genetic and learned information is transferred through time by genetic and cultural inheritance. As people interact with their environment they change natural and cultural fitness. Reciprocal changes and feedbacks between humans and their environment lead to coevolved human and natural cultures (Marzluff and Angell 2005).

The scientific community is just beginning to address the philosophical and methodological implications of defining a theory of urban ecology. Some scholars have suggested that we need a distinct theory of urban ecology to understand ecological patterns and processes in the urban ecosystem because humans are qualitatively different from other organisms (Trepl 1995). Trepl (1995) points out that a theory of urban ecology should explicitly address what distinguishes urban ecosystems from other types, and that it should outline the systematic relationships among these characteristics. He suggests a set of hypotheses concerning integration, succession, and invasion. First, in urban ecosystems the degree of integration among urban habitat patches and communities (i.e., organization or connectivity) is low, the systems are not in equilibrium, and stochastic processes predominate over deterministic ones (Trepl 1994). Second, succession is strongly linked to site history and is relatively unpredictable since urban ecosystems are not deterministically directed by functional dynamics. Moreover, cities are open to invasions by unknown numbers of alien species.

Others have argued that humans are like other organisms, and therefore ecological theory can be extended to encompass human-dominated environments (Niemala 1999). Urban ecosystems, according to Niemala (1999), differ from nonhuman-dominated ones in the degree of influence of human activities (Gilbert 1989, Sukopp and Numata 1995, Walbridge 1997). Niemala (1999) argues that the basic ecological patterns and processes in human- and nonhuman-dominated ecosystems are similar, and there is no need for a distinct theory of urban ecology. Thus, we can successfully study urban ecosystems using existing ecological theories, such as metapopulation theory (Niemala 1999).

Do we need a distinct theory of urban ecology to understand ecological patterns and processes in the urban ecosystem (Trepl 1995), or can we instead extend ecological theory to encompass human-dominated environments (Niemala 1999)? Collins et al. (2000) are more cautious in drawing a conclusion. Increasing evidence shows that the differences are not merely quantitative, but qualitative. There are also plausible explanations for leaving the question open. Collins et al. (2000) argue that several factors–including the influence of culture, the constraints and opportunities afforded by our institutions, and our ability to create strategies in response to anticipated selection pressures–mean that standard ecological and evolutionary theories and principles might apply only imperfectly to human populations.

The answer, I think, depends on how we define “urban ecosystem.” If we define it as a coupled human-ecological system, I propose that neither urban theory nor ecological theory can fully explain how urban ecosystems work within their separate disciplinary domains. As several authors have suggested, we cannot define coupled human-ecological systems either as humans embedded in an ecological system or as ecosystems embedded in human systems (Westley et al. 2002, Walker et al. 2004, 2006). How, then, can we synthesize our existing knowledge into a set of hypotheses that can inform the development of a theory of urban ecosystems as coupled human-ecological systems?

Building on previous work that applies complex system and hierarchy theory to coupled human-ecological systems (Levin 1998, Wu and David

2002, Holling 2001, Holling et al. 2002a, Gunderson and Holling 2002, Walker et al. 2004), I propose a framework to identify significant properties that govern the functioning of urban ecosystems. I propose that urban ecosystems are hybrid, multi-equilibria, hierarchical systems, in which patterns at higher levels emerge from the local interactions among multiple agents interacting among themselves and with their environments. They are prototypical complex adaptive systems, which are open, nonlinear, and highly unpredictable (Hartvigsen et al. 1998, Levin 1998, Portugali 2000, Folke et al. 2002, Gunderson and Holling 2002). Disturbance is frequent and intrinsic (Cook 2000). Change has multiple causes, can follow multiple pathways, and is highly dependent on historical context (Allen and Sanglier 1978, 1979, McDonnell and Pickett 1993). Agents are autonomous and adaptive, and change their rules of action based upon new information.

We can use a set of heuristics to describe these characteristics of urban ecosystems, and articulate formal hypotheses about their functioning and dynamics. Based on an extensive review of the literature on coupled human-natural systems, in this book I have identified eight elements that characterize urban ecosystems: (1) hierarchies, (2) emergent properties, (3) multiple equilibria, (4) non-linearity, (5) discontinuity, (6) spatial heterogeneity, (7) path-dependency, and (8) resilience.

Hierarchies. Urban ecosystems can be described as near-decomposable and nested spatial hierarchies, in which hierarchical levels correspond to structural and functional units operating at distinct spatial and temporal scales (Levin 1992, Reynolds and Wu 1999, Wu and David 2002). In the urban landscape, the lowest hierarchical level and the smallest landscape spatial unit vary with socioeconomic and biophysical processes from households and buildings to habitat patches or remnant ecosystems. At a coarser spatial scale land parcels and habitat patches interact with each other to create a new functional level and unit such as a neighborhood or sub-basin. Neighborhoods and sub-basins initiate and are constrained by regional economic and biophysical processes. Since landscapes are non-linear systems, they can simultaneously exhibit instability at lower levels and complex meta-stability at broader scales (Wu 1999, Burnett and Blaschke 2003). Near decomposability is a key tenet of hierarchy theory; ecological systems can be simplified based on the principle of time-space to simplify the complexity of nature, yet retain its essence (Wu, 1999). Urban landscapes are also hierarchically organized. At the higher levels, processes occur on a larger spatio-temporal scale and define the boundary conditions in which the system functions; at the lower levels, processes are faster and local and act as initiating conditions. In applying hierarchical theory to urban ecosystems, holons (horizontal structure) can be represented by patches (the ecological unit) and parcels (the economic unit). Through loose horizontal and vertical coupling, patches and parcels interact with and between other patches and parcels at the same, and at higher and lower, levels of organization (Wu 1999).

Emergent properties. Urban ecosystems exhibit emergent properties: properties that do not belong to any of their component parts. In emergent phenomena, a small number of rules or laws can generate complex systems and behaviors through local-scale interactions. Ecosystem stability and resilience emerge from the self-organized interaction of many different ecological processes occurring at different scales (Peterson et al. 1998). Similarly, self-organizing principles can also be applied to spatial economies to understand the clustering of land uses (Krugman 1995). The economics of urban systems and their spatial competition may lead to a clustering of similar land uses, while monopolistic competition can lead to their spatial dispersal (Parker et al. 2001). A more complex question is how to identify the emergent properties of coupled systems. Urban landscape patterns emerge from local-scale interactions among variables such as human preferences for residential location, individual mobility patterns, transportation infrastructure, and real estate markets, but also regional climate, hydrology, and topography (Torrens and Alberti 2000).

Multiple equilibria. No ecosystem has a single equilibrium; instead, multiple equilibria define functionally different states and contribute to their persistence and their self-monitoring and self-correcting capacity. Multiple equilibria are an emergent property of the coupled human-natural system. Urbanization can drive urban ecosystems to a state of sprawl. As urbanization increases, the system moves between natural vegetation attractors and sprawl attractors. The system moves away from the natural vegetation attractor toward the sprawl attractor and beyond, until increasing urbanization reduces the system's ability to support the human population. In urbanizing regions, as human services replace ecosystem services, the ecosystem reaches a threshold where it is likely to collapse. If the ecosystem collapse has reduced settlement enough to allow substantial natural vegetation to regrow, this process drives the system back toward the natural vegetation attractor.

Nonlinearity. An essential aspect of complex systems is nonlinearity (Levin 1998). A system is considered nonlinear if its outputs are not proportional to its inputs across the range of the inputs. In nonlinear systems, a very small change in some parameters can cause great qualitative differences in the resulting behavior. In complex systems, the system parts may interact strongly, leading to the emergent properties. In urban ecosystems interactions between human and ecological systems may lead to sharp shifts in behaviors when an unstable equilibrium threshold is crossed. Traffic flow patterns, urban development and decay, and sprawl are examples of nonlinear system behaviors.

Path dependency. Current driving forces can only partially explain current landscape patterns. Most changes in complex adaptive systems are reinforced by local chance events, such as mutation and environmental variation, leading to potential alternative developmental pathways (Levin 1998). Landscape change may depend on initial conditions, and small random events may lead to very different outcomes. Nonlinearity leads to path dependency. That is, the local rules of interaction change as the system evolves and develops (Levin 1998). One example of path dependency is the effect of transportation infrastructure on the pattern of development, through both increased development and changes in the real estate market, that in turn affect further infrastructure development (Turner et al. 1995).

Discontinuity. In ecosystems, change is neither continuous and gradual nor consistently chaotic. Rather it is episodic; periods of slow movement are punctuated by sudden change (Holling et al. 2002b). Moreover, events vary widely in the way they occur over space and scale (Holling 1973, O'Neill et al. 1988, Levin 1992). Discontinuities arise in an endogenous way, i.e., from within ecosystems (Holling 1973). An example is the spruce budworm (*Choristoneura fumiferana*) and its outbreaks in Canadian forests which periodically defoliate and kill large areas of mature balsam fir (Holling 1978b, Ludwig et al. 2002). Multiple equilibria dynamics and discontinuities occur also in coral reefs (Hughes 1994) and kelp forests (Estes and Duggins 1995). Discontinuities have also been documented in coupled human-ecological systems (Carpenter et al. 2002, Holling 2001, Holling et al. 2002a, Rosser 2006). Examples are fishery collapses, discontinuities in forestry, and eutrophic shallow lakes (Schindler 1990, Scheffer 1998, Carpenter et al. 2002, Wagener 2003).

Spatial heterogeneity. Events are not uniform over space (Holling 1978a). Landscape patchiness is a well known phenomenon, although as Turner and Chapin (2005) remind us, ecology still lacks a theory of ecosystem function that is spatially explicit. We do know that spatial variations in biophysical factors (e.g., topography) and disturbance determine the natural matrix of spatial variability in ecosystems (Holling 1992). Species patchiness, for example, can be caused by one of two different phenomena: the positive spatial autocorrelation of the ecological spatial processes of individual organisms (e.g., dispersal, competition) or spatial dependence due to species responses to underlying environmental conditions (Wagner and Fortin 2005). In urban ecosystems the sources of heterogeneity are multiple, and are generated by both human decisions and ecological processes (Band et al. 2005).

Resilience. Resilience is the capacity of a system to absorb shocks without reorganizing around a new set of structures and processes. More precisely, Holling (1973) defines resilience as the amount of disturbance a system can absorb without shifting into an alternate regime. In urban ecosystems, resilience depends on the ability to simultaneously support human and ecological functions (Alberti and Marzluff 2004). When thresholds are exceeded, the system shifts to a new regime that may be reversible, irreversible, or effectively irreversible—that is, not reversible on human time scales (Scheffer et al. 2001, Carpenter 2003).

Urban ecosystems provide unique opportunities to test hypotheses about interactions between humans and ecological processes. Using the heuristics proposed above, I suggest we can develop and test several hypotheses to study urban ecosystems and understand complex phenomena such as sprawl. The synthesis I have proposed in this book of the rapidly growing empirical work by multiple research teams on urban ecology points to five major themes: 1) Urban ecosystems are dynamic, hierarchically structured, patch mosaics resulting from local interactions between human and biophysical agents. 2) Urban ecosystems are likely driven between multiple states by the amount and pattern of urbanization (Alberti and Marzluff 2004). 3) Spatial interactions between socioeconomic and biophysical patterns and processes in urban ecosystems lead to emergent properties (e.g., sprawl). 4) Emergent landscape patterns affect ecological and socioeconomic processes in nonlinear ways (e.g., the intermediate disturbance hypothesis). 5) Ecosystem functions (both ecological and human) are moving targets with multiple and unpredictable futures; thus, policies that aim to achieve fixed goals cause a loss of resilience and are destined to fail.

10.3 Building Integrated Models

Complex systems theory (CAS, Levin 1998, 1999, Gunderson and Holling 2002) provides the theoretical framework for linking the local interactions between human dynamics and ecological processes to the overall structure and dynamics of urban landscapes. Drawing on *hierarchy theory*, urban landscapes can also be modeled as nested hierarchies with vertical (levels) and horizontal (holons) structures (O’Neill et al. 1986, Wu 1999, Wu and David 2002). Wu and David (2002) hypothesize that while the dynamics of urban landscapes are primarily driven by bottom-up processes, top-down constraints and hierarchical structures are also important for predicting these dynamics. I propose that a *multi-agent modeling* system can provide a platform for integrating these approaches and modeling the agents, the environment through which agents interact, and the rules that define both the relationships among agents and the relationships between agents and the environment.

Important progress has been made in modeling dynamic multi-agent human and ecological systems, but no one has formally tested hypotheses about the interacting emergent behaviors of coupled human and ecological systems. There are several research challenges. First, how can we simulate emergent behavior in ways that reasonably capture the patterns observed in urban landscapes? Second, how can we explicitly represent the human and biophysical agents at a level of disaggregation that allows us to explore the mechanisms linking patterns to processes (Portugali 2000)? Third, in modeling the interactions between human and natural systems, we find that many factors operate simultaneously at different levels of organization (Alberti 1999a). Simply linking these models in an additive way may not adequately represent the behavior of the coupled systems because interactions may occur at hierarchical levels that are not represented (Pickett et al. 1994). Additionally, since urban landscapes are spatially heterogeneous, changes in driving forces may be relevant only at certain scales or in certain locations (Levin 1992, Turner et al. 1995). At present, however, we understand too little about the interactions between spatial scales. To simulate the behavior of urban ecological systems we will need to explicitly consider the temporal and spatial dynamics of these systems, and also identify the interactions between human and ecological agents across the different temporal and spatial scales at which various processes operate (Alberti 1999a).

To address the inherent complexity of urban systems, we will need to integrate many complementary research strategies. Urban ecosystems are conceptualized as nested hierarchies where individual domains (e.g., scales in landscapes) occasionally interact with domains at higher and lower levels; the strongest and most frequent interactions occur within one level (Allen and Starr 1982). Domains in the hierarchy are separated by different characteristic rates of processes and thresholds (abrupt changes in system processes; i.e., Meentemeyer 1989, Wiens 1989). At higher levels, we observe slower rates and larger entities; at lower levels we see faster rates and smaller entities (Wu 1999). The theory of *patch dynamics* provides a framework to address spatial heterogeneity and explicitly represent the structure, function, and dynamics of patchy systems (Levin and Paine, 1974, Pickett and White 1985, Wu and Levin 1994, 1997, Pickett and Rogers 1997). An *agent-based* structure makes it possible to model decision-making processes and integrate the different approaches into a coherent modeling framework.

I propose that we use pattern-oriented modeling (POM, Grimm et al. 2005) to test alternative models of underlying processes and structures, thus making agent-based modeling of urban ecosystems more rigorous. Patterns contain information about essential underlying processes and structures, and the strategy of POM can decode the information about the internal organization of the system. Users of this approach begin by observing patterns at multiple scales and testing hypotheses about agent behaviors and interactions across scales. The assumption is that for complex systems, a single pattern observed at a specific scale and hierarchical level is not sufficient to understand a system or to reduce the uncertainties in model structure and parameters (Grimm et al. 2005). Pattern-oriented modeling can reduce uncertainty in model parameters, both by making models structurally realistic, which usually makes them less sensitive to parameter uncertainty, and by making parameters interact in ways that resemble the interactions of real mechanisms. It is therefore possible to fit all the calibration parameters by finding values that reproduce multiple patterns simultaneously (Grimm et al. 2005, Wiegand et al. 2003).

10.4 A Research Agenda for Urban Ecology

While various schools of urban ecology have developed alternative models to integrate human and ecological systems, they all point to the same need: we must redefine the set of questions that will guide the next generation of urban ecological inquiry. Redman et al. (2001) ask: “How did the social-ecological system develop into its current state, and how will it change in the future?” The focus here is the system: the nature of feedback, the rates of change, system components, and the specifics of resource use and production. Three associated questions further focus their inquiry. 1) How have the characteristics of ecological systems in the region under study influenced the social patterns and processes that have emerged? 2) How have social patterns and processes influenced the use and management of ecological resources? 3) How are these interactions changing over time and what does this mean for the state of the social-ecological system? (Redman et al. 2001).

With my colleagues in the UW Urban Ecology Program (2003, 1176), I emphasize a slightly different focus: “How do humans interacting with their biophysical environment generate emergent collective behaviors (of humans, other species, and the systems themselves) in urbanizing landscapes?” We ask four questions: 1) How do socioeconomic and biophysical variables influence the spatial and temporal distributions of human activities in human-dominated ecosystems? 2) How do the spatial and temporal distributions of human activities redistribute energy and material fluxes and modify disturbance regimes? 3) How do human populations and activities interact with processes at the levels of the individual (birth, death, dispersal), the population (speciation, extinction, cultural or genetic adaptation), and the community (competition, predation, mutualism, parasitism) to determine the resilience of human-dominated systems? 4) How do humans respond to changes in ecological conditions, and how do these responses vary regionally and culturally (Alberti et al. 2003)?

Urban landscape patterns as emergent phenomena

A new research project at the University of Washington (UW) and Arizona State University (ASU), funded by the National Science Foundation (NSF) as part of the Biocomplexity Program, investigates the complex coupled human-natural system dynamics of the Seattle and Phoenix metropolitan areas (Alberti et al. 2006b).[2] The study aims to empirically test hypotheses about how the interactions of human agents, real estate markets, built infrastructure, and biophysical factors drive current patterns of development and how these patterns affect human and ecological function in these two different bioregions. The study employs a pattern-oriented hierarchical approach to model how complex agent-based interactions generate landscape patterns at multiple times and spatial scales. We address four overarching questions: 1) How do dynamic landscape systems evolve to generate the emergent patterns that we see in urban landscapes? 2) What nonlinearities, thresholds, discontinuities, and path dependencies explain the divergent trajectories of urban landscapes? 3) How do emergent urban landscape patterns influence biodiversity and ecosystem functioning? 4) How can urban planning integrate this knowledge to develop sustainable urban landscape patterns? (Alberti et al 2006).

This project is one of several that have started to articulate key research questions so we can begin to test hypotheses and develop a theory of urban ecosystem dynamics that is crucial if urban ecology is to advance as a science. Our project is still at its beginning stage, and after completion we expect that it will only start to shed some light on these fundamental questions, but we believe that the questions we pose provide a useful starting point to develop a research agenda for urban ecology.

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[2] BE/CNH: Urban Landscape Patterns: Complex Dynamics and Emergent Properties (Alberti PI: BCS 0508002). The project is a joint effort by the UW Urban Ecology Research Lab (www.urbaneco.washington.edu) and the ASU Global Institute of Sustainability (http: //sustainable.asu.edu/gios/).

1) How do coupled human-ecological systems evolve to generate emergent patterns that we see in urban landscapes?

What agents, processes, hierarchies, and interactions govern the emergence of these patterns? How do spatial interactions among the human and biophysical processes lead to emergent properties? In the Biocomplexity Project we hypothesize that distinctive urban landscape patterns are associated with alternative states of urban ecosystems (Alberti and Marzluff 2004). These patterns can be characterized as highly developed vs. undeveloped land cover, clustered vs. dispersed development, specialized vs. mixed land use, and high vs. low level of urban infrastructure. Operationalizing the questions posed above into a set of testable hypotheses requires explicitly modeling 1) the agents, 2) the interactions among and between agents and their environment through time and space, and 3) the dynamic changes resulting from the interactions. We hypothesize that urban landscapes are spatially nested hierarchies in which hierarchical levels correspond to structural and functional units. Using a hierarchical modeling approach, we aim to identify the structural and functional units at distinct spatial and temporal scales of human and biophysical processes and specify the agents and rates of processes that characterize and distinguish the levels in the hierarchy.

2) What nonlinearities, thresholds, discontinuities, and path dependencies explain divergent trajectories of urban landscapes?

What are the multiple equilibria in such systems? Dynamic complex systems are typically characterized by two or more possible system states (defined either at a specific point in time or as a developmental trajectory) to a given set of inputs and boundary conditions (Levin 1999, Gunderson 2000, Gunderson and Holling 2002). In a *state* space defined by all the variables or components of a system, we define the region of the space to which all the evolutionary trajectories are drawn as an *attractor* or *basin of attraction*. We hypothesize that urban landscapes are likely driven between the natural vegetation and sprawl states by the amount and pattern of urbanization (Alberti and Marzluff 2004). We propose that the emerging pattern mediates the relationship between urbanization and movement between states.

What are the sources of nonlinearities, thresholds, and discontinuities in the relationships between human and biophysical systems that explain the pattern in the landscape? A system is considered nonlinear if its outputs and inputs are not proportional across the range of the inputs. Urban landscapes exhibit characteristics of nonlinear systems. In this project we explore the sources of nonlinearities, including thresholds, self-reinforcing and self-limiting processes, self-organization, hysteresis and the multiple adjustments in the interactions between human and biophysical processes that lead to emergent properties.

How are urban landscape trajectories shaped by prior conditions? Current driving forces can only partially explain current landscape patterns. Landscape change may depend on initial conditions, and small random events may lead to very different outcomes. An example of path dependency is the way transportation infrastructure affects the pattern of development by leading to increased development and changes in the real estate market. The resulting development also feeds back into further infrastructure development (Turner et al. 1995). We hypothesize that trajectories of landscape change result from the phenomenon of "lock-in systems" (Turner et al. 1995).

3) How do emergent urban landscape patterns influence human and ecosystem functioning?

Current NSF studies in three major urban regions-Seattle, WA, Phoenix, AZ, and Baltimore, MD–are starting to articulate hypotheses about some unique characteristics of human-dominated ecosystems and their functioning including their biogeochemistry and trophic dynamics. Urban ecosystems exhibit properties that might be distinct from nonurban systems as a result of fragmentation of natural habitats, altered hydrological systems, human-controlled energy flow and nutrient cycles, and their consequences on trophic interactions. Urbanization favors some species, but selects against others so that the composition of urban communities differs from those found in native environments. However, we do not know how patterns emerging in urbanizing regions affect biodiversity, since empirical tests of mechanisms controlling ecosystem functions have been primarily conducted in non-human-dominated ecosystems.

The challenge for urban ecology is to start to formalize hypotheses that link patterns to processes in urbanizing regions. Marzluff and his colleagues find the highest bird diversity in Puget Sound landscapes that have intermediate levels of disturbance in the form of urban development and a mosaic of forested landscapes (Alberti and Marzluff 2004, Marzluff 2005, Hansen et al. 2005). These results are consistent with the "intermediate disturbance" hypothesis (Blair 1996, 2004), but we still do not understand the specific mechanisms that cause these patterns of diversity to emerge. In our Biocomplexity Project, Marzluff and his team aim to explore how patterns in avian demographics (survival, reproduction, and dispersal) emerge as across the urban-to-rural gradient.

Since urban ecosystems are characterized by both ecological and human functions, we can expect important feedback mechanisms between ecological and human processes to control ecosystem dynamics. Ecological changes at local and regional scales affect human well-being and preferences as well as the decisions people make. Assessing the resilience of urban ecosystems requires understanding how interactions between human and ecological processes affect human functions such as housing, water supply, transportation, waste disposal, and recreation. Ecosystems provide important services to the urban population: they regulate climate, control flooding, and absorb carbon, to mention a few (Ehrlich and Mooney 1983, Daily 1997, Costanza et al. 1997). One important trajectory of future research is to articulate how emerging patterns in urban ecosystems affect household preferences and land development choices.

4) How can urban planning integrate emerging knowledge about human-ecological systems to develop resilient urban landscapes?

The questions that motivate urban ecology research are important to public policy because of the multiple challenges facing policy makers: they must plan and manage urban ecological systems in ways that minimize the ecological impacts on ecosystems while sustaining economically and socially viable urban communities. We aim to generate empirical knowledge and to develop tools that can inform decision-making and support the assessment of alternative strategies and investment decisions in the processes of urban development and ecological conservation.

10.5 Implications for Urban Planning

A systematic understanding of the relationships between human and ecological processes in urban landscapes is central to urban design and planning. In response to the costs of sprawling development patterns, urban planning has attempted to stabilize inherently unstable states in urbanizing regions by devising plans and strategies that aim to achieve a balance between the conversion of natural land cover and the maintenance of ecological conditions that support human services (Alberti and Marzluff 2004). The assumption behind planned development and smart growth is that urban development patterns affect the ability of the natural processes and built infrastructure to support human and ecological function in urban areas. An understanding of how alternative development patterns can simultaneously support ecological (i.e., bird diversity, water quality) and human function (housing and water supply) seems essential to guide planning practice, especially given that urban patterns are being further decentralized.

It is also critical to understand how coupled human-ecological systems work if we are to more effectively target questions that are relevant to policy decisions. More than ever, urban policymakers are challenged by the task of redirecting urban growth towards a more sustainable course. To do so, they expect scholars of urban ecology to answer fundamental questions about the ecological resilience of alternative urban patterns. However, as we have seen throughout this book, the study of coupled human-ecological systems in urbanizing regions is still too fragmented to let us answer such questions—and it lacks a fully integrated theoretical framework.

The challenge, as I pointed out at the beginning of this chapter, is for both ecology and urban planning. It implies the development of a hybrid theory of the urban phenomena. While urban analysts have been interested in the question of appropriate urban form for more than a century, only since the 1950s have they recognized the need for a theory of urban form. Kevin Lynch and Lloyd Rodwin (1958) were the first to stress the importance of an analytical framework to link human goals to city form, and then to sketch the elements of one (Alberti 1999c). In their incisive article "A Theory of Urban Form," they developed analytical categories to explore the relationships between elements of form and basic values such as health, survival, growth, and adaptability. Although they developed a general model that would apply to various human values, as the values would be continuously redefined, so would the analytical system (Alberti 1999c).

Lynch's *Good City Form* (1981) is the first complete theoretical exploration of how urban patterns perform in relation to specific human values. Since then, society's goals have changed profoundly as scientists have learned far more about human interactions with the environment. We now recognize that human and environmental systems interact in very complex, often nonlinear ways, on multiple scales of time and space (Holling et al. 2002a). But this knowledge is not reflected in urban theory and practice. If we are to analyze the city as a complex system that evolves in response to changes in both socioeconomic and biophysical forces, we will need not only to extend our current approaches but also to integrate modes of inquiry combining historical, comparative, and experimental approaches (Alberti 1999c).

I suggest six implications of coupled human-natural systems. First, urban planning must fully appreciate that coupled human-ecological systems are dynamic, open, and non-equilibrial. This has implications for developing and evaluating urban planning strategies and the ability of the ecosystem to maintain or recover ecological function after development. Instead of aiming at achieving a specific condition (e.g., fixed urban density or distance of a development from a stream, as set in most planning regulations), planning must aim at maintaining the characteristics of the system that simultaneously support ecological and human function (i.e., resilience). Furthermore, if variability rather than consistency characterizes ecological conditions, multiple urban patterns might be "desirable" under different ecological conditions as opposed to a single "optimal" one.

Second, we need to recognize that change in coupled human-ecological systems can occur abruptly and discontinuously. We can characterize this response by drawing on thresholds and multiple domains of stability. As Holling (1996) suggests, knowledge of the system is always incomplete and surprise is inevitable. This perspective on environmental change requires a new framework for both understanding and including surprise as we explore and plan for resilient urban patterns. Typically planning relies primarily on predictive models, but complexity and uncertainty of coupled human-ecological systems make their interactions highly unpredictable. By focusing on key drivers, complex interactions, and irreducible uncertainties, scenario planning generates plausible futures within which predictive models can be used to test hypotheses and develop adaptive management strategies.

Third, we must see biophysical processes as drivers of urban change. Since human and ecological systems are interdependent—humans affect ecosystems functions, and ecosystem change simultaneously affects human well-being. Therefore we will have to extend urban theory to include an understanding of how urban systems respond to changes in the biophysical structure. The idea of a city being interdependent with its regional natural resources is not new to planning theory (Geddes 1905). What is new is considering the urban ecosystem as a coupled human-ecological system that evolves through the dynamic interactions between human and ecological functions. Ecosystems provide essential services to urban areas. When ecosystems change—watersheds are contaminated, biodiversity is lost, or climate changes—human well-being is affected over the long term.

A fourth implication is the importance of investigating mechanisms and thresholds. Where significant relationships exist between urban patterns and ecosystem functions, we must investigate the mechanisms that explain the relationships and explore whether the functional relationship indicates the existence of thresholds. John Marzluff and I (Alberti and Marzluff 2004) hypothesize that patterns of urbanization are critical in balancing the tension between providing human and ecological services and maintaining the unstable equilibrium created by planned development. We must learn more about the dynamics of these relationships so we can understand the factors that determine such thresholds of changing patterns.

A fifth implication concerns the consideration of scale. The relationship between urban patterns and ecological function depends on scale. Of course the study of urban patterns and ecological resilience must apply to the scales of both the city and metropolitan area—but urban patterns are relevant to environmental processes operating at multiple scales. Scale considerations include both the resolution of a given urban pattern measurement and the geographic extent or boundary of the area being considered. To study the relationships between urban patterns and human and ecological functions, we will have to cross spatial and hierarchical scales. Therefore, we need a nested approach.

A sixth implication is that the unpredictability of today's urban ecosystems challenges traditional planning and management assumptions and strategies for natural resources and environmental conservation. Planning and management strategies that aim to achieve a stable state are likely to make the system less resilient and reduce the options for sustaining human and ecological functions simultaneously. For urban planning and management practices to succeed, they must take complexity and uncertainty into account and redirect strategies toward building flexibility, adaptability, and resilience (Gunderson and Holling 2002). The challenge is to develop an adaptive capacity to learn and incorporate such knowledge in managing change.

10.6 A Final Note

In this book I have intentionally not resolved one key dilemma: whether we need to develop new ecological and urban theories, or whether we can extend current theories to describe how urban ecosystems work. We must learn much more before we can resolve this question; in fact, I leave it to my students and their students. It will take another generation of thought and scholarship before we will understand what kinds of dual and hybrid knowledge we need to achieve an effective synthesis between humans and nature in cities. Several scholars have tried to resolve the dilemma by proposing that the need for fundamentally novel theories to study urban ecosystems does not exclude disciplinary perspectives from playing a valuable role. But, as several others have started to articulate, a successful theory of urban ecology will require a number of specialists to think in interdisciplinary and multidisciplinary ways (Collins et al. 2000).

The task, I think, goes beyond the natural and social sciences to include the arts. Cities are the product not only of natural history and human activity. They are also the product of human imagination. In Italo Calvino's *Invisible Cities* (1974) Marco Polo describes the city of Fedora to Kublai Khan. The city's museum contains crystal globes that hold miniature representations of the city as individual inhabitants imagined it might have become but did not. As sociologist Howard Becker (2002) points out, Calvino's dialogues with Kublai Khan have important epistemological implications for our theories about the world. Her reading of Calvino's methodology is highly relevant here. A unified theory of urban ecology has to find room for both the "true" Fedora and the little Fedoras in the glass globes. "Not because they are equally real, but because they are all only assumptions. The one contains what is accepted as necessary when it is not yet so; the others, what is imagined as possible and, a moment later, is possible no longer" (Calvino 1974, 32). Marco Polo suggests that in order to understand general rules that apply to the city, "we must exclude [from the number of imaginable cities] those whose elements are assembled without a connecting thread, an inner rule, a perspective, a discourse" (Calvino 1974, 43-44). But Calvino (44) warns us that "Cities also believe they are the work of the mind or of chance, but neither the one nor the other suffices to hold up their walls." That is, neither is a sufficient explanation of how they work (Becker 2002). For that reason perhaps a "unified" theory of urban ecology will never exist, and many will argue that aiming at one will defy the mysteries of how urban ecosystems actually work and evolve.