5

Resilience in Hybrid Ecosystems

VARIABILITY AND CHANGE ARE VITAL TO THE PERSISTENCE AND EVOlution of ecosystems. Studies of complex systems have uncovered direct relationships between variability in systems' structures and their resilience. Change—both slow and fast—is integral to the workings of any natural system. This chapter articulates the hypothesis that variable patterns of urbanization and modular urban infrastructure may be key to cities' resilience. I use three examples—carbon, nitrogen, and bird diversity—to illustrate the complex relationships between patterns of development and key slow and fast variables that regulate resilience in urban ecosystems. I argue that policies and management that aim to achieve stable conditions by optimizing only one system function at one scale may make systems more vulnerable and could eventually lead to their collapse.

Resilience in hybrid ecosystems is an emergent property of co-evolving human and natural processes. We cannot understand the diverse expressions of present urban landscapes unless we consider the complex history of interactions between humans and nature over millennia. The collapse of the Mayan cities during the eighth or ninth century—still quite an enigma—has only recently been investigated from the perspective of coupled human-natural systems by integrating empirical evidence from different fields. A plausible hypothesis is that a severe drought, exacerbated by rapid deforestation and desertification in a time of unprecedented population density, led the Mayans to abandon urban sites in the Yucatán region (E. Cook, Hall, and Larson 2012). Complex interactions between human and natural processes are also key to understanding the resilience of old cities, including Rome and many others in the Mediterranean region, that have survived the test of evolving nature and civilizations. The landscape stratification that we can see in Rome today reveals how humans and nature co-evolved over nearly 2,800 years of change: ecological, economic, social, cultural, and political. To explain the structure, dynamics, and evolution of emerging ecologies in urban ecosystems—whether we are interested in the biodiversity of New York's Central Park or Moscow's Bitsevsky Park, or in the biogeochemistry of Seattle or Phoenix—we must acknowledge their hybrid nature.

Although scholars of urban ecology have recognized the evolutionary nature of urban ecosystems and acknowledged their unique hybrid dynamics for some time, most empirical research is still grounded in divided paradigms. The knowledge that emerges from these paradigms is incomplete in a fundamental way. Emerging studies of coupled human-natural systems reveal new and complex patterns and processes that are not evident when social or natural scientists study them separately (Liu et al. 2007a). For the past few decades, teams of biologists, earth scientists, economists, geographers, and planners have expanded our understanding of urban ecosystems by uncovering key mechanisms that characterize coupled human-natural dynamics in urban regions (Alberti et al. 2003; Grimm et al. 2000; Pickett et al. 2001).

Several important findings have emerged from this work (Alberti 2010; Grimm et al. 2008a; Pickett et al. 2011). Cities have a distinctive biogeochemistry because infrastructure that is engineered to move water and remove wastes alters hydrological processes and nutrient cycles (Kaye et al. 2006). Densely urbanized areas also have unique microclimates, such as heat islands, which influence atmospheric chemistry and air pollution (Grimm et al. 2008b). Evidence also suggests that the distinctive compositions of plant and animal species found in cities are strongly influenced by human perceptions and behaviors (Faeth et al. 2005). But these specific findings do not add up to an understanding of how such systems work and evolve; we must uncover the rules governing community assembly.

One critical aspect of such an understanding is learning how the structures of urban ecosystems (i.e., diversity of components and degree of connectivity) relate to their dynamics. That is, which qualities best express and regulate function and change in hybrid systems? Recent evolution in complex science has begun to uncover direct relationships between complex network structures and their resilience. Scheffer et al. (2012) noted that two key qualities of system architecture—*heterogeneity* and *modularity*—might determine the likelihood of critical transitions and the emergence of thresholds and system shifts (i.e., a catastrophic bifurcation).

Variability and change are two essential characteristics of ecosystems. It is the great variability found in nature that explains persistence and evolution. Change, whether gradual or abrupt, is integral to the way nature works. Emerging evidence shows that complex networks in which components vary and connectivity is incomplete tend to have greater capacities to adapt than those characterized by highly connected homogeneous elements. Interactions among components that are relatively independent allow them to change and evolve in an autonomous way.

In this chapter, I articulate the hypothesis that heterogeneity and modularity of urban structures may be key to cities' resilience: their ability to adapt to changes in ecosystems and in human communities. I challenge the dominant assumption of traditional urban planning that one optimal pattern of urbanization is consistently more resilient than another. I propose that policies and management that apply fixed rules for achieving predictable, stable conditions by optimizing one function at one scale may, in fact, make systems more vulnerable and eventually lead to their collapse. By simulating the effects of managing short-term variance in three models of ecosystem services—lake eutrophication, harvest of a wild population, and yield of domestic herbivores on a rangeland—Carpenter et al. (2015b) show how interventions to decrease variance might create ecosystem fragility by changing the boundaries of safe operating spaces and cancelling signals of declining resilience. A paradigm of co-evolution between humans and nature may prove more appropriate for learning how cities work and adapt to change.

Resilience in Hybrid Systems

It is critical to establish empirical evidence about the relationships among structure, dynamics, and resilience in urban ecosystems in order to advance sustainability science and effectively address emergent problems facing cities across the world. Holling (1973) defined *resilience* as the capacity of a system to absorb disturbance from change and reorganize while maintaining essentially the same functions, structure, identity, and feedbacks. Ecological resilience in urban ecosystems is governed by complex interactions between human and ecosystem functions over multiple scales and involving multiple heterogeneous agents (Alberti and Marzluff 2004; Peterson, Allen, and Holling 1998). We must include these complex interactions and agents when we study such systems. If we are to understand systems dynamics and potential shifts, it is not sufficient to consider human and ecosystem functions separately, because integrated socioeconomic and ecological systems behave differently than their separate parts. Furthermore, since urban development patterns affect the amount and pattern of built and natural land cover and the demand for natural resources to support human activities, alternative urban development patterns (e.g., urban form, land use distribution, and connectivity) may have differential effects on resilience. The challenge to effective planning and management of coupled human-natural systems is to expand our knowledge of their dynamics, resilience, and capacity to adapt and of their potential variability across regions and scales.

In 2004, John Marzluff and I described how, as ecosystems become urbanized, they move between two basins of attractions or stable equilibria: a natural state dominated by natural processes and an urbanized state dominated by humans (figure 5.1). As a region urbanizes, ecological processes supporting the urban ecosystem may reach a threshold and drive the system into an unstable state. Eventually the system shifts to a new state in which ecological processes are highly compromised and drive the system to collapse. We defined the resilience of an urbanizing region as the system's ability to maintain both types of functions simultaneously.

Urban rivers are an informative example of the evolving legacy of disturbance and system dynamics in urbanizing regions. Regime changes in river systems, and in their ecosystem functions associated with human action, have been described by several scholars looking at key geomorphological, hydrological, and ecological processes across a gradient of urbanization (C. J. Walsh et al. 2005; Vietz, Walsh, and Fletcher 2015; Hopkins et al. 2015) (figure 5.2). Over the past decade, we have learned a great deal about the complex interactions between changes in river functions and changes in land use and infrastructure.

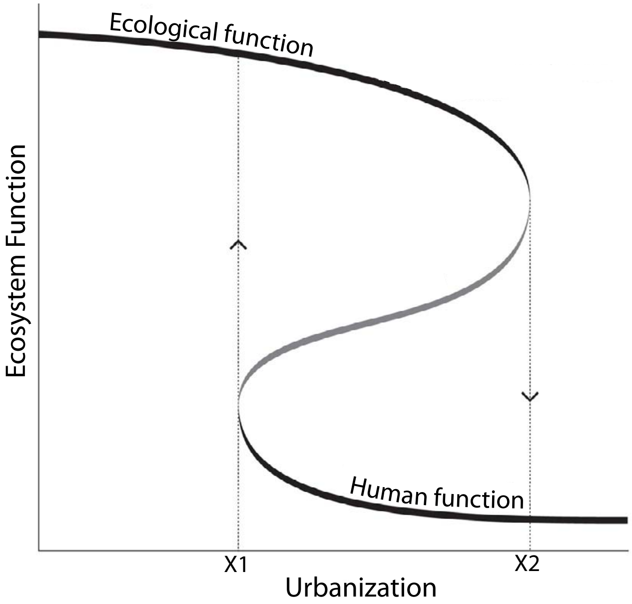
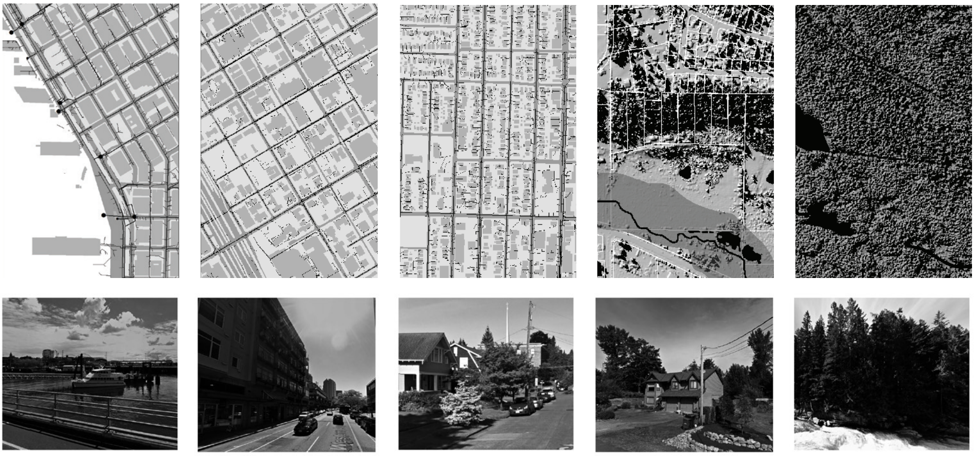


FIGURE 5.1 Dynamics in urban ecosystems. As a region urbanizes, ecological processes supporting the urban ecosystem may reach a threshold (X2) and drive the system into an unstable state. Eventually the system shifts to a new state in which ecological processes are highly compromised and drive the system to collapse. Alberti and Marzluff 2004.

Through a variety of human activities, urbanization affects hydrology and the pathways, rates, and frequency of water movements in a watershed, as well as associated sediment budgets and stream channels. Changes in the physical template may interact with external changes such as climate change and may drive regime shifts in the ecology of a stream. Although, to date, the best-known examples of system shifts in urban rivers involve geomorphic or hydrologic phenomena (Dent, Cumming, and Carpenter 2002), more recent studies have pointed out positive feedback mechanisms in stream ecology. In urban streams, riparian and in-stream vegetation may play a critical role in creating and maintaining distinct alternate states that are characterized by markedly different ecological communities and processes (Heffernan, Sponseller, and Fisher 2008; Stanley, Powers, and Lottig 2010).



Combined sewer overflow and outfalls; Waterfront

Underground pipes and lateral drains; CBD

Gutter and street drains; Residential neighborhood

Swales and retention ponds; Exurban development

Infiltration and natural waterways; Intact forest

FIGURE 5.2 Urban hydrology has implications for urban infrastructure across a gradient of urbanization. Maps (*left to right*): LiDAR Top Surface DEM 2003: King County, Washington (2003); infrastructure, sewer, and drainage: City of Seattle 2012; property/survey: building outlines (City of Seattle 2012), street/transportation: City of Seattle 2012. All photographs: Google Maps 2015.

Researchers have documented more and more examples of regime shifts (see the Regime Shifts Database, www.regimeshifts.org). More recently, they have described several examples in urbanizing regions (e.g., urban lakes, invasive species, and floods), but we still do not fully understand the significance of such dynamics. In particular, we do not know the extent to which patterns of urbanization might mediate relationships between urban stressors and ecosystem functions and resilience.

Resilient Urban Patterns: A Hypothesis

Increasing numbers of studies show that patterns of urbanization have differential effects on ecosystem functioning, and that those patterns may mediate ecosystem responses in subtle and unexpected ways (Bang, Sabo, and Faeth 2010; Faeth et al. 2005). The hypothesis that patterns of urbanization influence ecosystem function relies on the assumption that several thresholds exist (figure 5.3a). The dominant view in urban

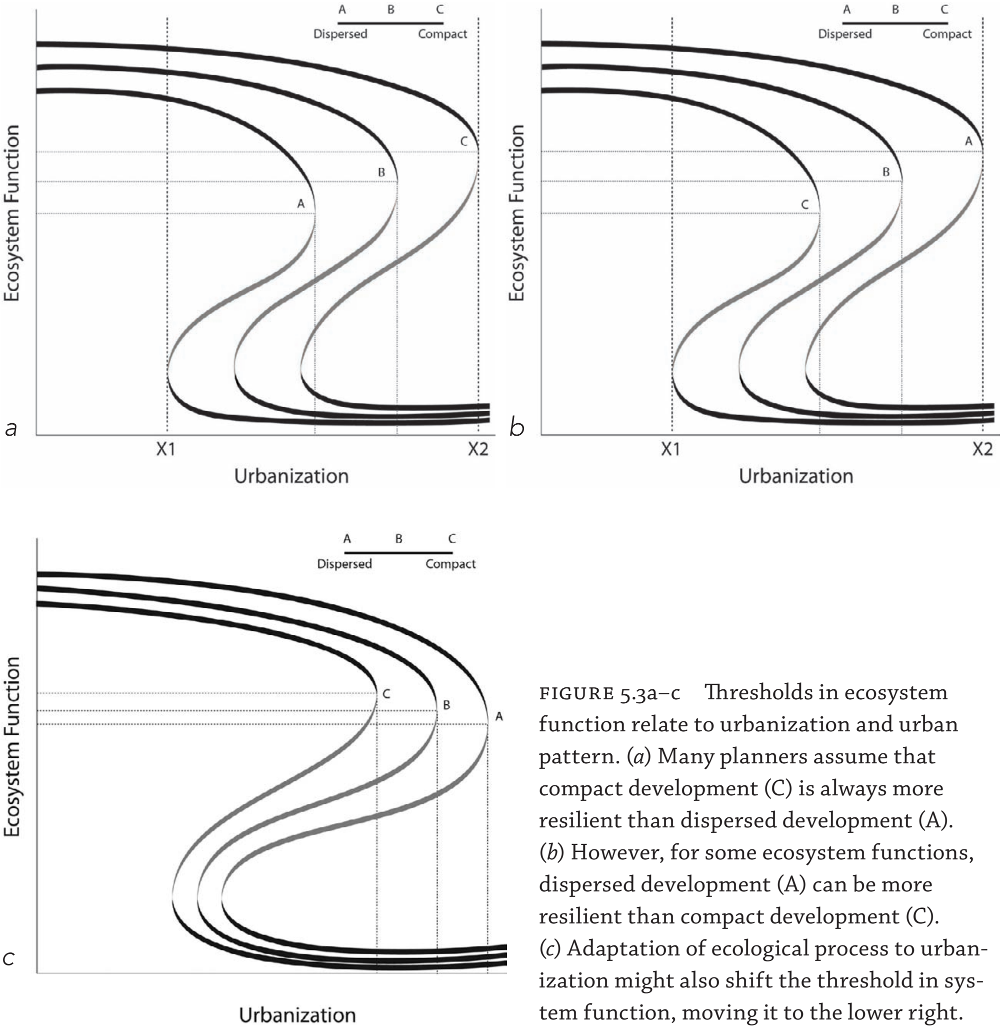


FIGURE 5.3a–c Thresholds in ecosystem function relate to urbanization and urban pattern. (*a*) Many planners assume that compact development (C) is always more resilient than dispersed development (A). (*b*) However, for some ecosystem functions, dispersed development (A) can be more resilient than compact development (C). (*c*) Adaptation of ecological process to urbanization might also shift the threshold in system function, moving it to the lower right.

ecological planning is that dispersed development (A) leads to a faster decline in system function compared to more compact forms of development (C) and that, therefore, compact development is more resilient (figure 5.3a). But because patterns of development have different impacts on the slow and fast variables that regulate system dynamics, the reverse can also be true: dispersed development can be more resilient than compact development under certain conditions and for certain ecosystem functions or scales (figure 5.3b). Also, we do not know whether adap-

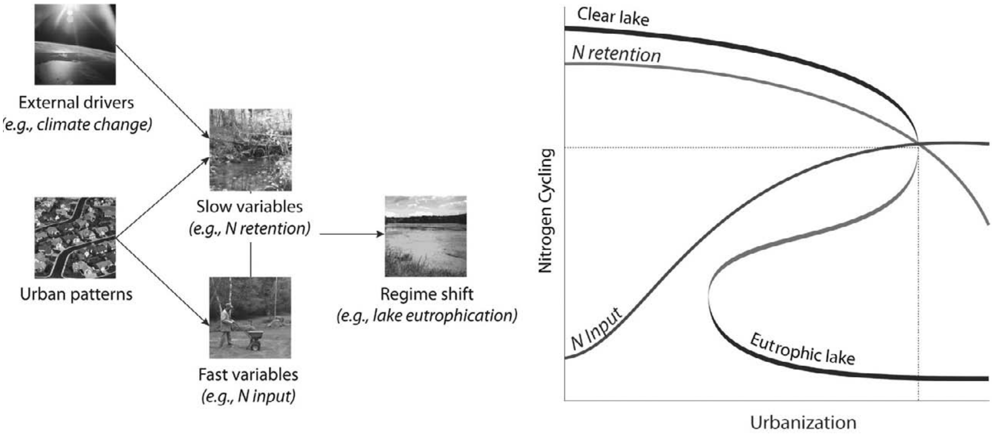


FIGURE 5.4 Urban patterns have complex impacts on *slow* and *fast* variables that control conditions in urban systems (e.g., lake eutrophication). Slow variables (e.g., N retention in urban watersheds) refer to factors that change gradually, in response to long-term processes, and constrain the ranges of responses of fast variables (e.g., nutrient inputs). Photographs: climate change: Michel; urban patterns: Sam Korson; N retention: Yortw; N input: CIFOR; lake eutrophication: Dave Blogg.

tation of ecological processes to urbanization would make an urban ecological system more resilient to urban stress. In figure 5.3c, this phenomenon is represented by the system transition thresholds moving to the lower right. The shifting thresholds depend on dynamics and tradeoffs that we do not fully understand; on variable human and environmental conditions; and ultimately, on future interactions among uncertain trajectories of key driving forces.

Urban patterns have complex impacts on what we define as *slow* and *fast variables* that affect system resilience. Slow variables are factors that change slowly in response to long-term processes (such as the growth of trees or the accrual of sediment) and that constrain the responses of fast variables, potentially generating or preventing a tipping point. Fast variables are factors that change rapidly and that managers find easier to measure. For example, the slow variables affecting nitrogen budgets in a watershed are factors that change gradually in response to long-term processes (such as nitrogen retention) and that constrain the responses of fast variables (such as nutrient input), generating a shift to a new state (such as lake eutrophication) (figure 5.4).

The question, then, is not simply whether patterns of urbanization matter. Rather, we should ask: If they matter, how do urbanization patterns influence key variables and mechanisms that affect different ecosystem functions? Three examples—carbon, nitrogen, and bird diversity—illustrate the complex relationships among patterns of development and key slow and fast variables that regulate ecological resilience. In using these examples, my intent is not to focus specifically on any individual pattern or function but to emphasize nonlinear relationships among mechanisms affecting fast and slow variables that control ecosystem dynamics along a gradient of urbanization.

Signatures of Hybrid Systems

I begin with the assumption that different patterns of development produce different landscape signatures (spatial and temporal changes in ecosystem processes) and that, in turn, these signatures influence patterns of urbanization (Alberti 2008). If we could build cities by replicating a single pattern for which we could determine per-capita land and emission budgets, perhaps we could find an optimum pattern for the urbanizing world. But cities do not conform to a single pattern. Instead, they exist along a complex dynamic gradient of evolving landscapes: what was the urban fringe in 1900 is today the dense urban core. The signatures of urban ecosystem functions vary along a hypothetical gradient of urbanization, ranging from the urban core (characterized primarily by urban redevelopment) to suburban and exurban areas (where rapid development is occurring) to rural and intact forest. Evidence shows that patterns of urbanization mediate these dynamics in subtle and unexpected ways.

Urban Carbon

Urban development directly and indirectly affects stocks of carbon (i.e., pools of carbon such as plants). It also affects carbon fluxes: exchanges between two different stocks, such as the transfer of carbon dioxide from the atmosphere to the biosphere via plant photosynthesis or in the opposite direction via combustion of organic matter. Land-cover change is only one of many processes linking urban development patterns to the carbon budget. Urban development typically involves an increase in the amount of impervious surface, which alters hydrology and reduces infiltration capacity. Impervious surfaces and human activities may also change the microclimate (Oke 1982). In addition, urbanization involves multiple pollution sources, including chemical inputs from industry, agriculture, and transportation. Finally, land-cover changes typically result in changes in the abundance and composition of plant species, which affects the rates at which carbon is assimilated.

Hypotheses about the variability of carbon stocks and fluxes along an urban gradient are grounded in mechanisms that are known to affect carbon stocks and fluxes (Canadell et al. 2003). Lucy Hutyra and I have identified five key mechanisms that affect change in carbon stocks and fluxes along a gradient of urbanization: land use, emissions, organic inputs, temperature, and nitrogen fertilization (Alberti and Hutyra 2013). Carbon fluxes include exchange processes that are both positive (uptake: photosynthesis and soil accretion) and negative (loss: respiration and emissions). Carbon fluxes typically respond and change on much shorter time scales (e.g., hours) than carbon stocks, which change as a result of long-term changes in fluxes on a time scale of years or longer.

Scientific knowledge of the shifts in water and life cycles occurring in urbanizing regions is grounded in nearly a century of research, but shifts in carbon cycles associated with urbanization—specifically the dynamics and trade-offs that control system variables—are far more recent and are not well documented. We do not know the magnitude of carbon stocks in urban areas. For example, in the Seattle metropolitan area, my research lab team found that the amount of live biomass aboveground far exceeds previous estimates of carbon stocks (Hutyra, Yoon, and Alberti 2011). Furthermore, nowhere is the uncertainty and complexity of linkages and thresholds more pervasive than in urban forests (Kaye et al. 2006; Pataki et al. 2006).

One confounding variable leading to these challenges is the ubiquitous relationship between carbon cycles across biomes (regions) and scales. In a temperate environment such as the Seattle metropolitan area, reduction in forest cover is a primary driver of carbon cycling (Hutyra, Yoon, and Alberti 2011). However, in desert environments such as the Phoenix metropolitan area, where irrigation has radically transformed urban vegetation from the presettlement vegetation, relationships between urban land use and ecosystem productivity are driven largely by human alterations to the availability of water. When legacies such as agriculture, transportation infrastructure, and geomorphology are combined with the uncertain trajectories of key driving forces such as technological innovation and climate change, they significantly reduce our capacity to predict the differential effects and mechanisms that will govern relationships between urban patterns and ecosystem functions.

The curves in figure 5.5 show effects on carbon stocks and fluxes per unit of biomass (*y*-axes) as they are expected to vary along an urban gradient (*x*-axes). Compared to the urban center, plants take up more carbon at the urban fringe and increasingly more in the exurban areas and forest end point in proportion to the total biomass per unit area. But emissions are also higher at the urban fringe because suburban residents drive more miles. Trade-offs may exist between stocks and fluxes. For example, in dispersed developments, households can maintain relatively more live biomass than they can in dense urban areas because land parcels are larger, but suburban residents may produce higher emissions of carbon dioxide because they commute farther.

Variations in the carbon budget across an urban gradient are a result of the gradient's influence on several mechanisms that govern the uptake, release, and storage of carbon. Hutyra and I hypothesized that stocks of carbon within vegetation will be higher as urban intensity decreases but that the changes will be nonlinear (Alberti and Hutyra 2013). We predicted that urban vegetative stocks of carbon will be lowest where development is most intense because green vegetation will be replaced with buildings and pavement. Carbon stocks in organic detritus are kept artificially low in urban areas because cities collect and remove leaves and debris, but we would expect the fluxes (input rates) to increase linearly across the urban-to-rural gradient (which is directly proportional to biomass and leaf area).

Carbon fluxes typically respond and change on much shorter time scales (e.g., hours) than do carbon stocks, which respond, on a time scale of years, to accumulated long-term changes in fluxes. We hypothesized that, per unit, more biomass carbon will be taken up in urban settings because of the favorable growing conditions: people will water, fertilize, and prune their plants, and they will replace native vegetation. And, in the most intensely urbanized areas, more carbon will be lost through the ecosystem's heterotrophic respiration (R_H) per unit of mass due to

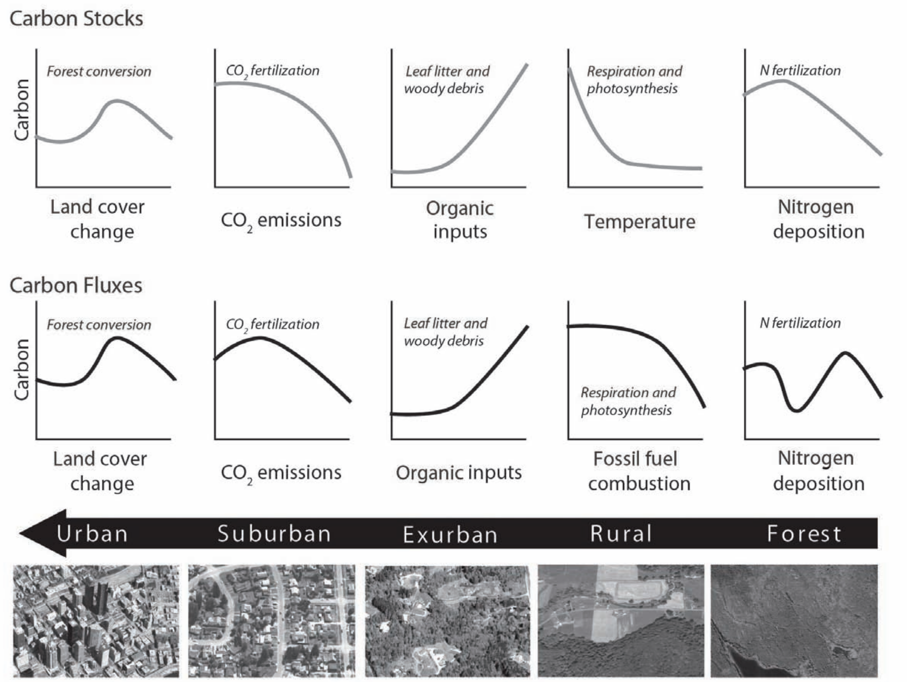


FIGURE 5.5 Hypotheses of mechanisms influencing carbon budgets along the urban gradient, showing variability of carbon stocks and fluxes per unit of biomass (*y*-axes). They are expected to vary along an urban gradient (*x*-axes) in relation to key mechanisms governing carbon uptake, release, and storage (Alberti and Hutyra 2013). Aerial photographs: Google Maps 2015.

increased temperatures and soil moisture, but the removal of organic inputs (leaf litter and woody debris) will reduce the amount of substrate (stock) for decomposition and result in an overall decrease in R_H per unit of area. Higher levels of estimated CO_2 emissions are generally associated with the greater vehicle miles traveled (VMT) of suburban residents, but actual CO_2 emissions associated with travel have been observed both at and around the urban core. As concentrations of CO_2 increase, autotrophic respiration (R_A) can be expected to decrease. Higher urban concentrations of ozone will also dampen carbon uptake rates (gross primary productivity, or GPP), but increased atmospheric CO_2 concentrations will increase GPP.

Taken together, we hypothesize that these five mechanisms will

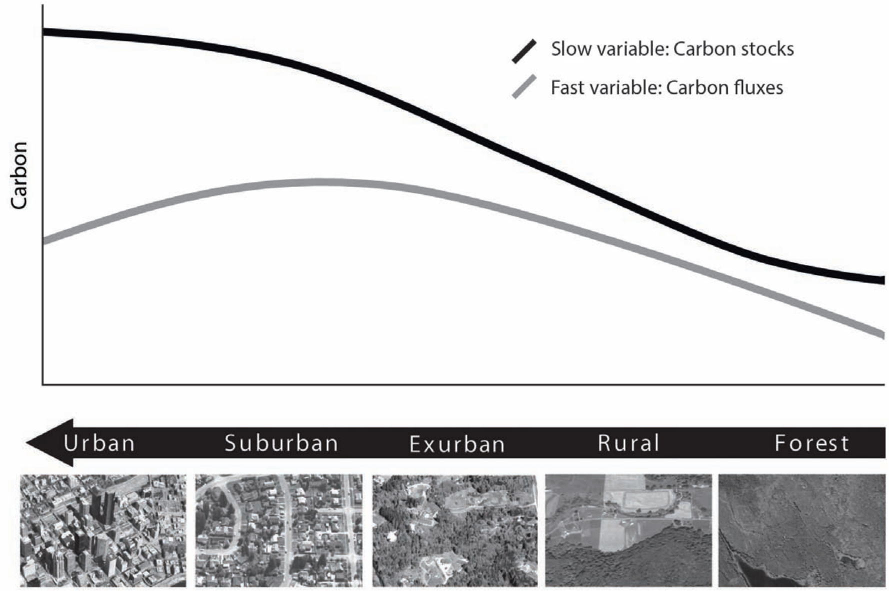


FIGURE 5.6 Relative impact of development on carbon stocks and fluxes. The slow variable (carbon stocks) is affected predominantly by dense development, while the fast variable (carbon emissions) is affected primarily by suburban development (Alberti and Hutyra 2013). Aerial photographs: Google Maps 2015.

produce nonlinear variations in carbon stocks and fluxes across the urban gradient (figure 5.6; Alberti and Hutyra 2013). The amount of carbon in vegetative biomass (and soils) is expected to generally increase with decreased development intensity, with a small peak in older suburbs and exurbs where larger lots have had time to accumulate biomass after they were initially cleared. Fluxes (per unit mass) might be expected to decrease with decreasing temperatures and decreased N and CO_2 fertilization, but, regardless of temperature, they ultimately will be highest in the least dense areas because of forests' high density of photosynthetically active vegetation.

Urban Nitrogen

Patterns of urbanization also affect the nitrogen budget in complex ways, through both changes in nitrogen input from multiple sources and changes in nitrogen retention. Nitrogen retention is affected by soil erosion and storm water, as well as by the extent to which nitrogen is present in a mobile form (e.g., fertilizer). It also can be taken up into biomass or denitrified, processes that depend on the temperature and available carbon. Nitrogen inputs depend on a combination of human activities that involve wastewater, fertilizer, and atmospheric NOx (figure 5.7).

The transition from forested or vegetated landscape to an urban landscape changes the relative contributions of these sources: from primarily atmospheric to wastewater, fertilizer, and possibly vehicle emissions inputs. Onsite septic tanks are found in more densely populated settings as suburban areas expand into the rural fringe. Higher densities of septic tanks can increase the levels of groundwater and of stream flow and, with them, nutrient concentrations (Sherlock et al. 2002). Impervious surfaces in urban areas are important pathways for accumulation of nitrogen, which is readily transported to water bodies (Collins, Sitch, and Boucher 2010).

Several mechanisms controlling soil's nitrogen content are potentially influenced by development, land-use legacies, and household landscaping practices: inputs (both intentional and unintentional), removal (of litter and debris), denitrification (conversion of nitrate to gaseous forms of nitrogen, which then diffuse back into the atmosphere), and movement of water out of yards (either through runoff to streams or infiltration to groundwater). Although residential developments in more urbanized areas tend to have high rates of nitrogen loading because residents apply fertilizer and deposit byproducts of combustion, people are also likely to remove litter and debris and convert land to impervious surfaces, activities that increase the amount and velocity of runoff. All this can result in loss of nitrogen. Residential parcels that were once farmland are likely to have comparatively high levels of soil nitrogen because of agricultural practices (Kaye et al. 2006). Household landscaping practices also frequently add nitrogen to the soil in the form of compost and synthetic fertilizers. On the other hand, removal of litter and debris may reduce nitrogen inputs, and frequent irrigation may enhance rates of denitrification and infiltration (Groffman et al. 2009).

I propose that the fast variable (nitrogen input) is affected primarily at the urban fringe due to the combination of nitrogen input from atmospheric deposition and fertilizer, while the slow variable (nitrogen reten-

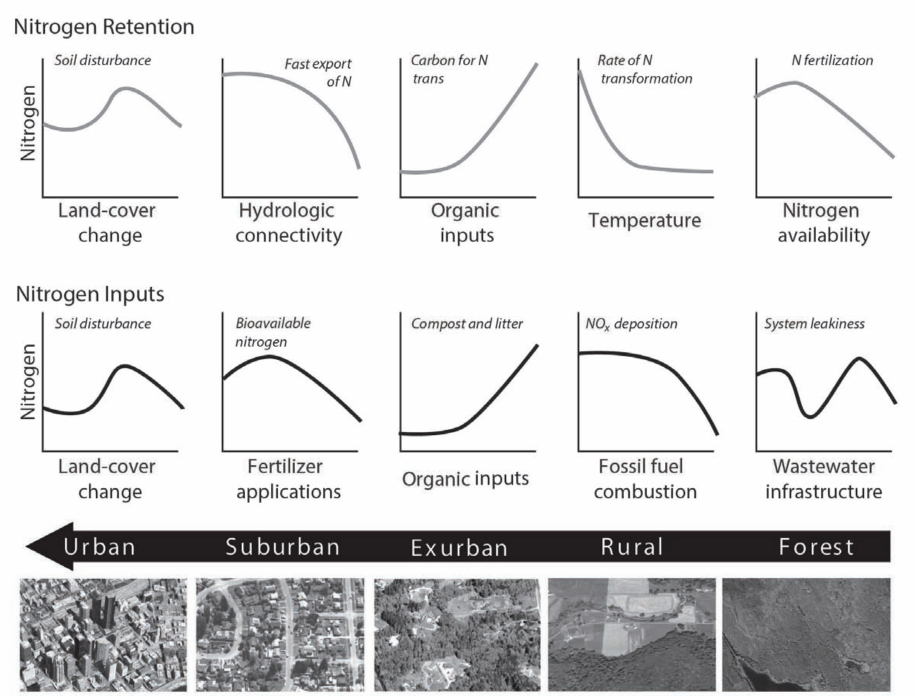


FIGURE 5.7 Hypotheses of mechanisms influencing nitrogen budgets along the urban gradient: The effects of urbanization on N budgets are mediated by complex interactions among fast and slow changes in N retention (represented by the upper set of curves) and N inputs (represented by the lower set of curves). Alberti and Larson 2011, personal communication; aerial photographs: Google Maps 2015.

tion) is significantly impacted at the urban core through highly connected impervious surfaces and pipes (figure 5.8).

Bird Diversity

Another example of this complexity is variability in bird diversity along an urban gradient, which involves the combined effects of loss of bird habitats (loss of forest cover and connectivity) and changes in biotic interactions, which lead to novel competitions. Complex interactions may emerge as habitats for native birds declines and humans create substitute habitats. Then new types of competition arise, resulting from the loss of native species coupled with colonization by early successional and synanthropic (thriving in human-altered habitats)

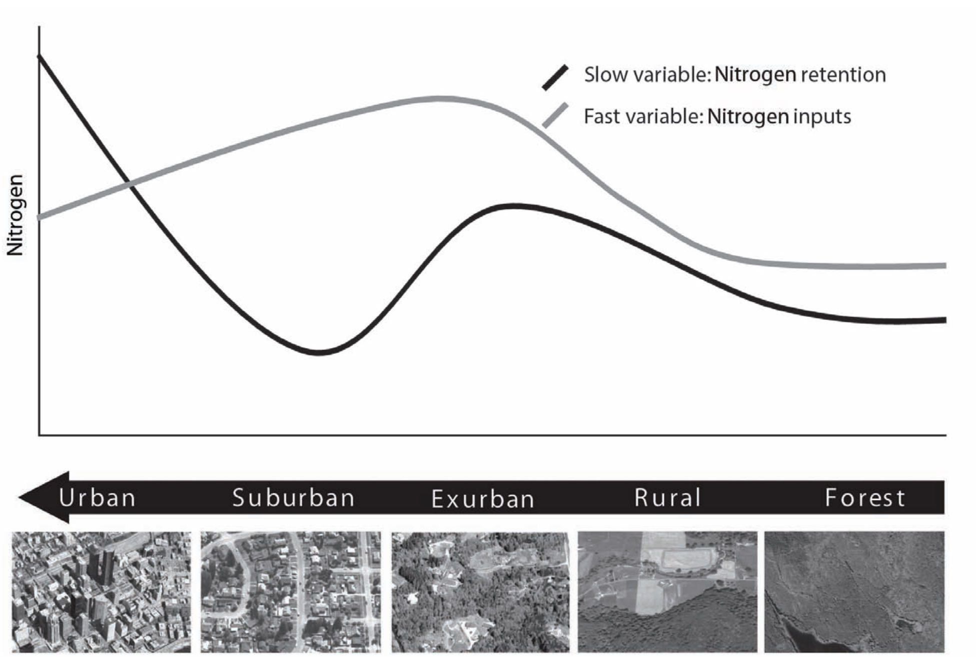


FIGURE 5.8 Relative impacts of development on nitrogen input and retention. Atmospheric deposition and fertilizer runoff affect nitrogen input (fast variable) primarily at the urban fringe, while at the urban core, N retention (slow variable) is mediated by connected impervious surfaces and pipes. Alberti and Larson 2011, personal communication; aerial photographs: Google Maps 2015.

species, which together generate a spike in the curve at the urban fringe (Marzluff 2005).

John Marzluff and I have developed a set of hypotheses to describe the complex interactions governing bird diversity across a gradient of urbanization. Figure 5.9 represents the hypothesized effects in relation to each mechanism as they vary along the gradient represented on the *x*-axis (Alberti and Marzluff 2013, personal communication). The *y*-axes vary according to mechanism. Rates of forest conversion and loss of native bird habitat are highest at the urban fringe, as forest conversion at the urban core has already occurred in the past. Forest connectivity declines as we move closer to the urban core. Food abundance is kept artificially high at the urban fringe because humans feed birds, but overall, it declines closer to the urban core. Disturbances increase with urbanization; we expect an increase in human-induced disturbances at and around the urban core.

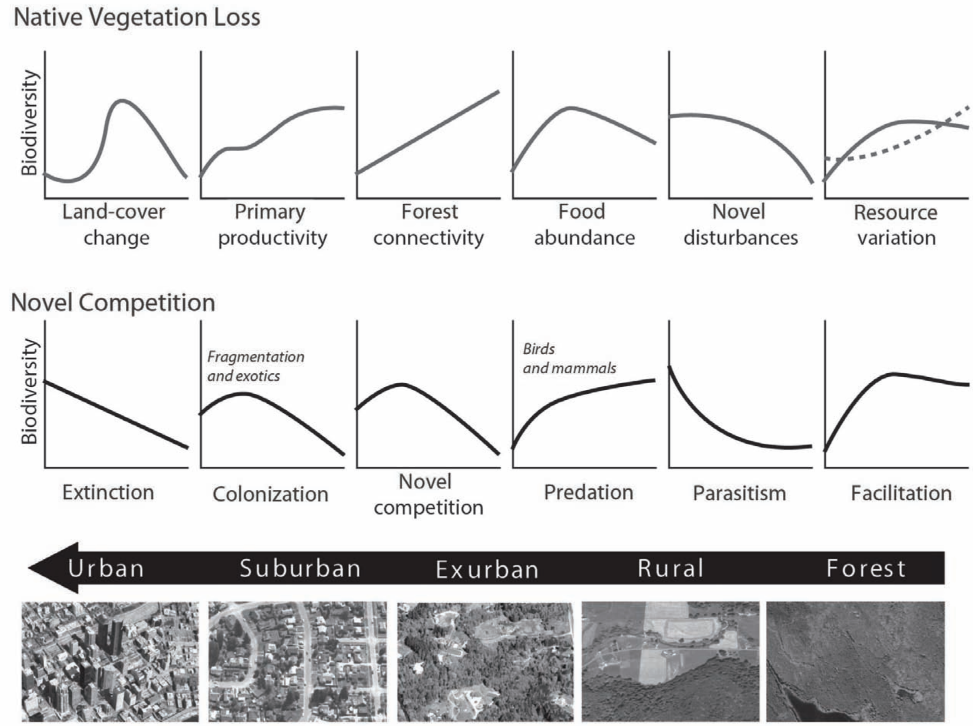


FIGURE 5.9 Bird diversity along urban gradients is governed primarily by impacts on natural habitat (fast variables) and biotic interactions (slow variables), though human supplementation of food supply can also play a role. (Alberti and Marzluff 2011, personal communication; aerial photographs: Google Maps 2015.

We can also expect different levels of variations in resources. Inputs of resources are replaced by human activities, and variation in resources may peak at the urban fringe, simultaneously reducing the variability of available resources; an example of this is the temporal variation in availability of food resources associated with rainfall patterns. Urbanization also alters mechanisms related to biotic interactions (Marzluff 2005). We expect a steady decline in native bird populations and an increase in extinction toward the urban core, while colonization by early successional and synanthropic species peaks at the urban fringe and then declines at the urban core. Predation from large mammals is expected to decline toward the urban core, but we do not expect a steady decline because urban pets also engage in a relatively substantial amount of predation (Marzluff

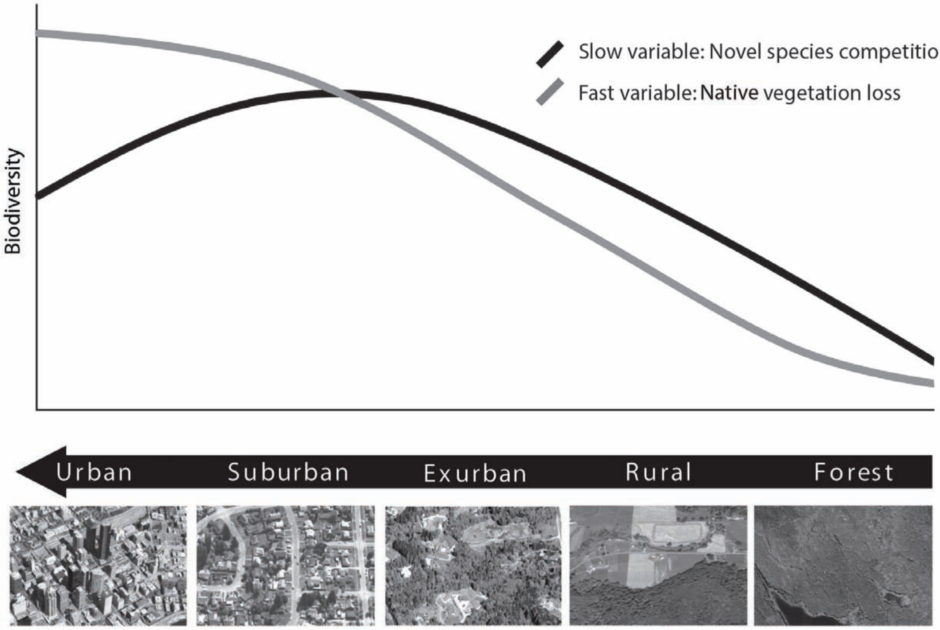


FIGURE 5.10 Relative impact of development on bird diversity. The fast variable (loss of native vegetation) is affected predominantly at the core, while the slow variable (increase in novel competition) is affected primarily by suburban development at the fringe. Alberti and Marzluff 2011, personal communication; aerial photographs: Google Maps 2015.

et al. 2007). We expect higher parasitism closer to the urban core. Humans may facilitate parasites in the suburbs (e.g., by putting out nest boxes). Insect species that are facilitated in "nature" by woodpeckers are facilitated in suburbs by woodpeckers, other birds, and people—for example, chickadees and swallows nest in nest boxes and lights. As diversity drops, some facilitators (e.g., large woodpeckers) might also drop out as their habitat is reduced and degraded. But we expect that this relationship will not be linear due to suburban activities; more likely, novel competitions will emerge as landscapes urbanize (Marzluff 2008).

Bringing these ideas together, I now highlight the nonlinearity (and perhaps the trade-offs), with respect to mechanisms affecting bird diversity, that exists across a gradient of urbanization (figure 5.10). Marzluff (2005) has found that, with increasing urbanization, changes in native bird habitat decline overall and that the relationships between bird diversity and the urban gradient do not adhere to a straight linear trend. At the urban fringe, the decline is less severe due to favorable growing conditions (e.g., human watering, fertilizer, pruning, and replacement of vegetation) and higher temperatures, but the decline increases with lower temperatures toward the fringe. Novel competition is higher farther from the urban core and peaks at the fringe because of subsidies and the relatively lower intensity of urban development. Of course, these mechanisms vary across biomes. We also hypothesize that tradeoffs exist between colonization by early successional and synanthropic species and retention of native species; these mechanisms control the overall species richness of different patterns of development.

Human Perceptions and Behaviors

Human preferences and behaviors also drive changes in ecosystem function (figure 5.11). Biogeochemical cycling and biodiversity in urban areas are affected by human decisions about where to locate homes and businesses and how to manage the landscape. Carbon budgets and avian community compositions in urban regions are the result of complex interactions between human decisions and natural processes. Human decisions have selective implications for species diversity and provide supplementary resources in urban areas as people water their gardens and feed birds. In return, biogeochemical cycling and biodiversity provide important ecosystem services and amenities to urban dwellers. Most often documented are the impacts of urbanization on land cover and the associated loss of vegetated cover, both of which have significant consequences for carbon and wildlife. But human perceptions and behaviors also modify ecosystem processes in more subtle ways.

Humans provide supplementary resources in urban areas by watering gardens and feeding birds, both directly and indirectly. Vegetated cover simultaneously provides habitat for birds, sequesters carbon, and serves as an amenity for urban residents. It is well known that the incremental value of vegetation increases as resources become scarce, but we are only beginning to fully account for the individual and collective benefits of vegetated cover and environmental quality for properties and neighborhoods.

Many aspects of urban form may influence the amount of carbon that

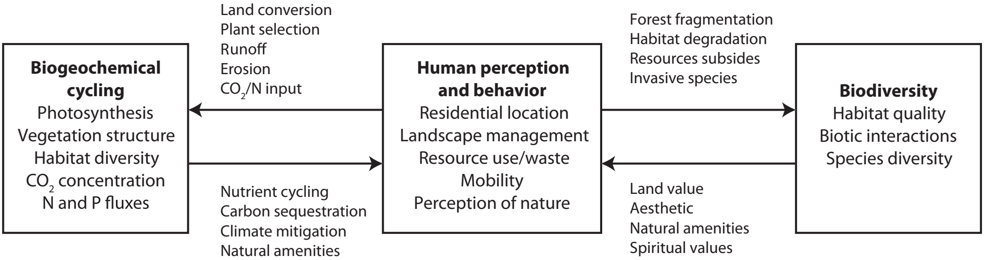


FIGURE 5.11 Human behavior. The fast variable (loss of native habitat) is affected predominantly at the core, while the slow variable (increase in novel competition) is affected primarily by suburban development at the fringe.

is emitted in urban areas (Pataki et al. 2006). Land can be developed in a wide array of patterns, based on variables such as form, density, land-use mix, and connectivity, and each pattern produces different rates of carbon emissions. A common assumption is that because suburban residents use their cars more than urban residents, they generate more vehicle miles traveled and therefore more emissions. But that assumption may not hold as urban regions become less monocentric in their development and job centers migrate beyond the urban core in response to increasing costs. Lucy Hutyra and I developed testable hypotheses about the carbon consequences of urban development by exploring linkages between urban form and carbon fluxes and by estimating the relative impact that alternative development patterns have on carbon fluxes across a gradient of urbanization (Alberti and Hutyra 2013). The impacts of carbon policies on residential and mobility patterns are difficult to detect because such policies are novel, and trends have yet to be observed over the long term. We expect that the complex dynamics between human perception and behaviors will generate nonlinear relationships between urban development and the key slow and fast variables that control the resilience of ecosystem functions.

Patterns of Resilience

Depending on alternative patterns, the trajectory of slow variables may constrain the impact of fast variables, either earlier or later in the process of urban development, by shifting the threshold associated with maintaining ecosystem function. This process is highly unpredictable and varies considerably under different bio-geophysical and socioeconomic conditions. It also depends on both ecosystem function (climate mitigation, biodiversity, biogeochemical cycling, etc.) and scale.

To achieve predictable and stable conditions, planning and management strategies tend to favor options that decrease variability of ecosystem processes over short time scales. Yet increasing evidence indicates that actions to decrease variance in ecosystems over short time scales may lead to long-term decline in ecosystem function (Carpenter et al. 2015b). Reducing short-term variance in ecological systems increases their variance in the long term. Evidence of how such phenomena, known as Bode's law, emerge in linear systems has been provided both in regulatory networks for ecosystem services (Anderies et al. 2013) and economics (Brock, Durlauf, and Rondina 2013). Along the same line, as I mention above, Carpenter et al. (2015b) have recently shown that reducing variance in nonlinear systems causes impact distributions to shift toward lower frequencies, leading to dynamical behavior changes and the risk of critical transitions.

In systems with multiple regime shifts, such as coupled socioecological systems, if one specific subsystem remains resilient at a specific scale, it may cause the entire system to lose its resilience in other ways. Urban mobility can be made highly efficient at the local scale by optimizing one type of transportation infrastructure, such as road transportation, while disinvesting in regional rail systems. A perturbation such as an unexpected shortage in gasoline or a spike in oil prices can result in system failure, however, simultaneously paralyzing multiple metro regions. The highly optimized tolerance (HOT) theory (Carlson and Doyle 2000) shows how due to robustness trade-offs, systems that are highly robust to frequent disturbances might become vulnerable to infrequent ones (Folke et al. 2010). If systems are to remain resilient, they must retain their adaptive capacity and their ability to cope with uncertainty across scales.

Predictability, Uncertainty, and Surprise

How do we deal with uncertainty and surprise? Consider, again, the hypothetical futures I described in the first chapter of this book, and imagine

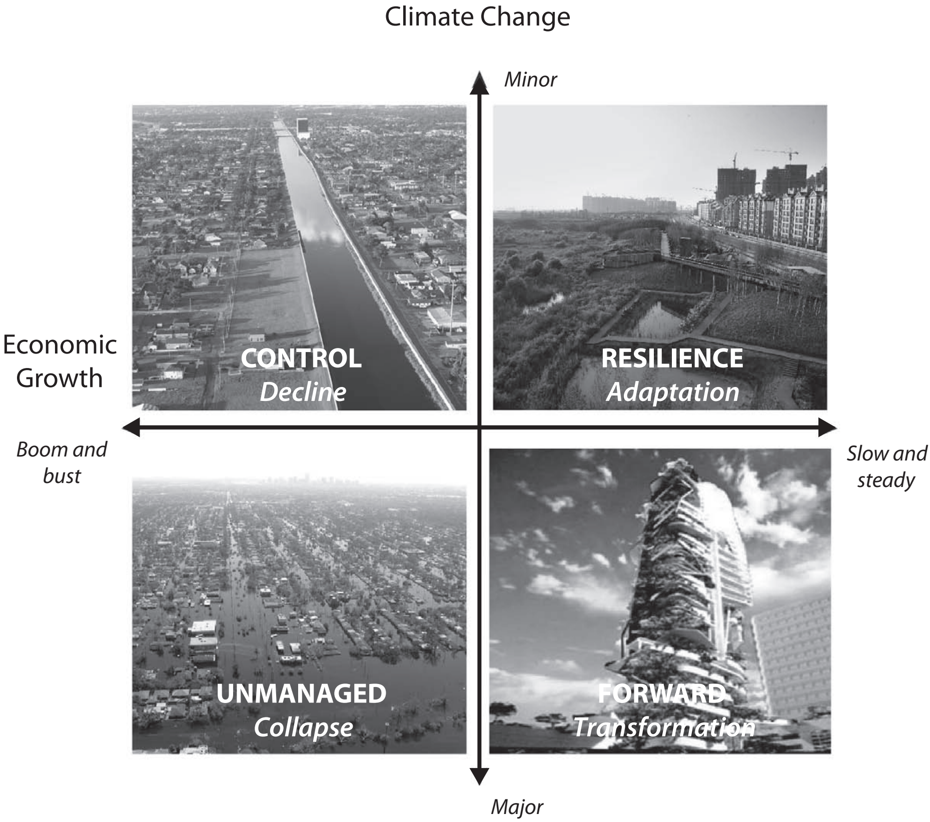


FIGURE 5.12 Hypothetical scenarios resulting from two uncertain variables: climate change (major versus minor) and the economy (boom and bust versus slow and steady). Photographs (*clockwise from upper left*): 17th Street Canal, David Grunfeld Landov Media; Qunli National Urban Wetland, Turenscape; EDITT tower, Hamzah & Yeang; Hurricane Katrina, National Oceanic and Atmospheric Administration.

four alternative scenarios (figure 5.12). Each of these futures results from the interactions of uncertain variables, such as climate change and the economy. How will they affect carbon and nitrogen budgets or biodiversity over the long term?

Looking at figure 5.13, we can imagine the dramatic difference that could result from major climate changes under an unstable boom-and-bust economy compared to a slow and stable one. At the upper left, we see that limited pressure from climate change, coupled with an unstable economy, might cause people to be less willing, and less able, to implement

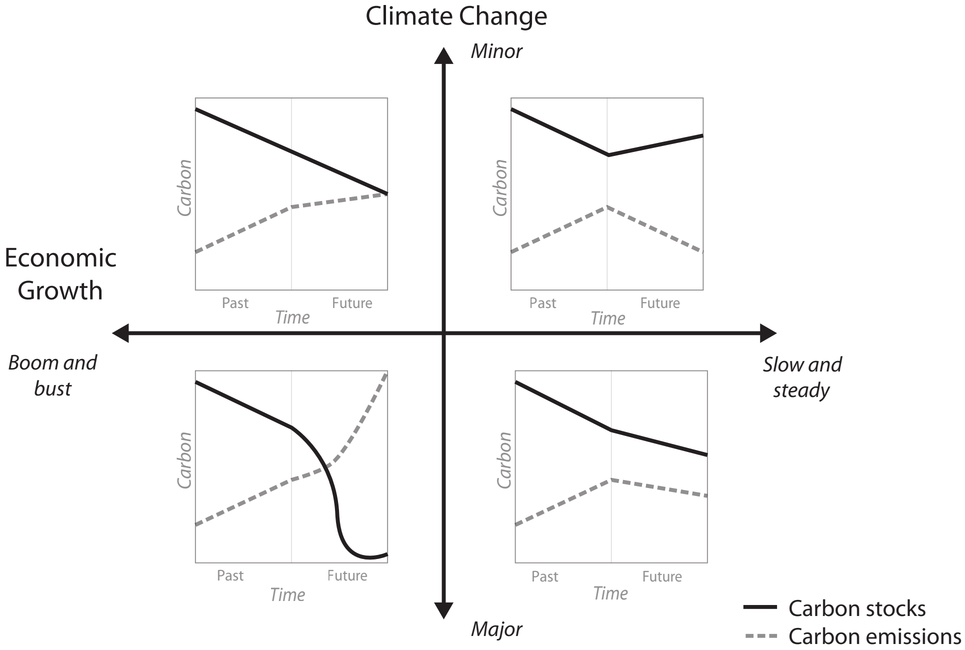


FIGURE 5.13 Hypothetical trends in the directions of slow and fast variables under plausible scenarios, showing substantial shifts from historical trends.

proactive conservation policies. Meanwhile, a stable economy, shown at the upper right, could lead to technological innovation. On the other hand, frequent perturbations from major climate impacts, coupled with economic instability, might lead to crisis and eventual collapse. Or, under a stable economy, they could instead lead to a completely different environment: one that encourages learning, innovation, and the emergence of new solutions.

Predictive models generate probabilities on the basis of observed dynamics. For example, we can estimate the probability distribution of carbon emissions given uncertain economic trajectories. But we cannot predict unexpected interactions among multiple uncertain driving forces, such as the possible trajectories that could result from interactions between major and minor climate change and a slow and steady versus an unstable boom-and-bust economy. Nor do we know the probability distributions of the impacts that could result from such interactions. The lower right quadrant of figure 5.14 shows that the actual impact could

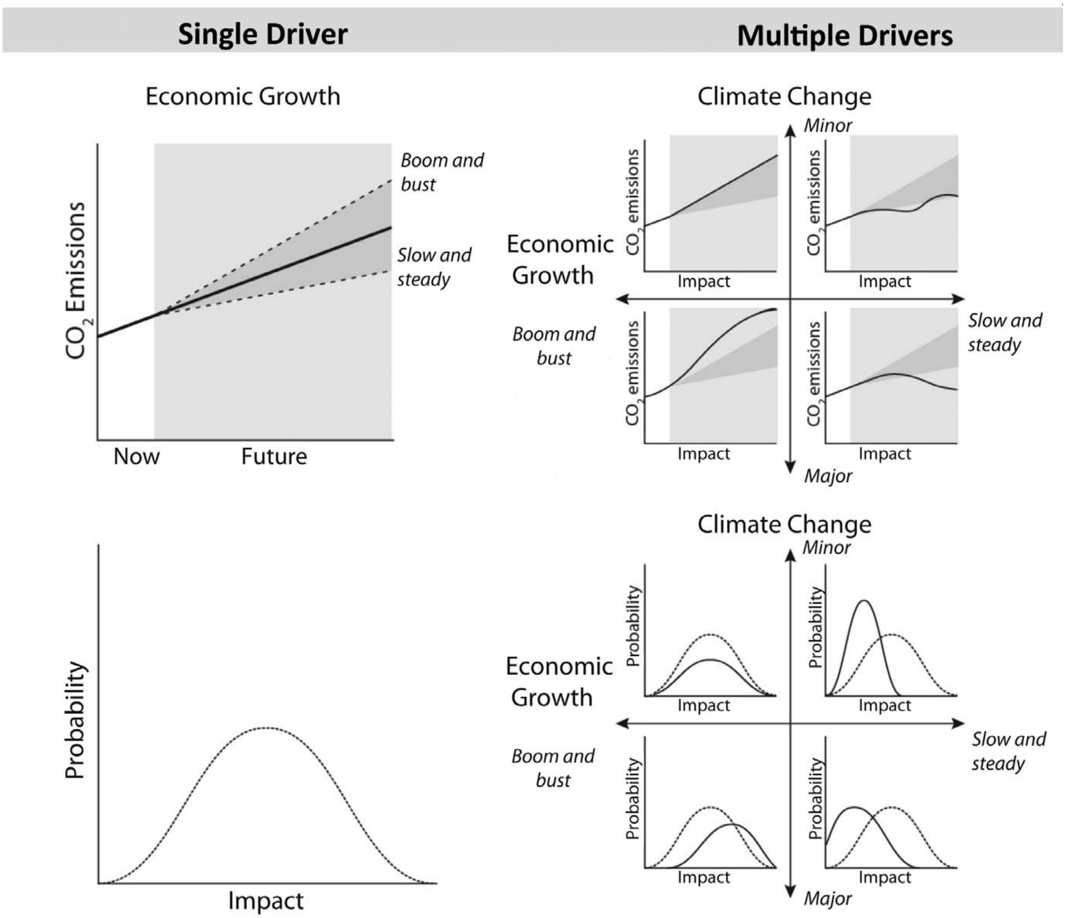


FIGURE 5.14 Probability distributions. The lower right graph shows that the actual impact of climate change could fall outside the predicted probability distribution of model projections (represented by the dotted lines).

very well fall outside of the predicted probability distributions of model projections (here represented by the dotted curves).

At the core of our challenge is the inevitable uncertainty of dynamic, coupled human-natural systems. Under plausible scenarios, trends in the directions of slow and fast variables could shift substantially from historical trends. For example, by assuming major climate changes and the boom-and-bust economy shown on the lower left, we can imagine rapid land conversion and an increase in logging; meanwhile, increasing energy

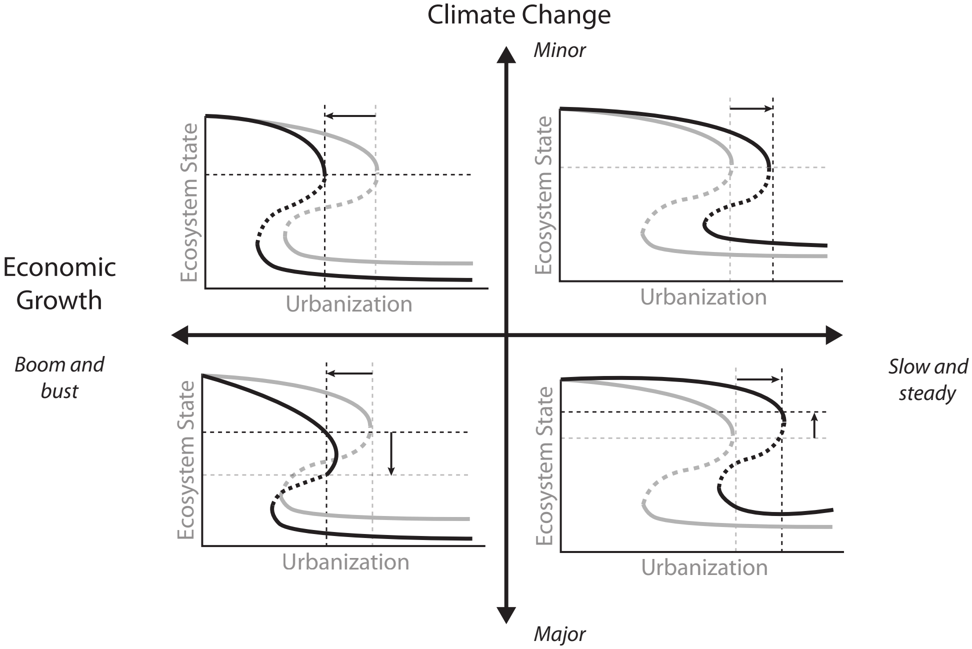


FIGURE 5.15 Hypothetical example illustrating how relationships between patterns of urban development and ecosystem function may vary under different scenarios.

demands and lack of regulatory power might lead to escalating emissions. Here the equilibrium curves associated with two alternative development patterns are represented under these plausible futures (figure 5.15). We might expect that the urban pattern would make dramatic differences for carbon stocks and fluxes and ecosystem resilience. But it might make no difference at all, depending on how these trajectories influence mechanisms and trade-offs among ecosystem functions across multiple scales.

Diversity and Modularity

I hypothesize that the diversity of patterns of urbanization maintained within a region and across regions might control the resilience of urban ecosystems (figure 5.16). Resilience depends on variable environmental and human conditions as well as on the unique history of each region. I suggest that the diversity of patterns might control resilience because

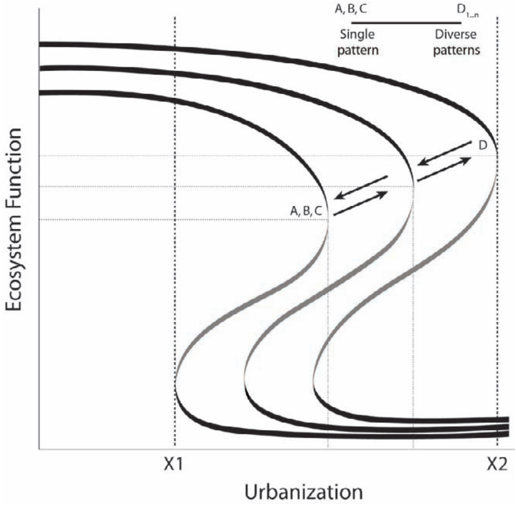


FIGURE 5.16 The diversity of patterns may control the resilience of urbanizing regions. A heterogeneous landscape composed of diverse patterns (D) is more resilient than any of the individual patterns.

this very diversity expands a region's capacity to adapt to a wider range of conditions and alternative futures. In the most recent examples of extreme climate events that tested the resilience of large urban regions across the world, the greatest surprises are in what worked (e.g., communication during Hurricane Sandy in 2013). Consider the countless ways in which unintended functions and flexibilities created by the diverse urban infrastructure (e.g., the transportation system) provided alternatives and ways out. An example is the vital role that bicycle infrastructure played during Sandy. With a flooded subway and shortage in gasoline, New Yorkers relied on the extended network of bike lanes, which provided them an alternative for commuting and allowed volunteers to bypass gridlocked traffic in their relief efforts. Most of all, they allowed communities to imagine ways to innovate and to adapt to rapidly changing conditions. Policies that aim at a single optimal pattern of urban development will eventually reduce the resilience of urbanizing regions in the face of uncertainty.

Implications for Planning: Emerging Principles

Planning agencies in urbanizing regions face unprecedented challenges: rapid environmental change places enormous pressure on their ability to support urban populations while maintaining a healthy ecosystem.

Agencies must make decisions about managing growth and investing in infrastructure while simultaneously providing human and ecosystem services. Strategic decisions about urban infrastructure and growth management are based on our assessment of the past and our expectations for the future. But complexity and uncertainty make the future increasingly unpredictable.

Climate change is expected to have significant impacts on essential human services (e.g., supplies of water and energy) and ecological functions (e.g., primary production) in urban areas. Potential regime shifts in coupled human-natural systems will inevitably surprise us. An inherent tension exists between resilience and transformation. How can planning help cities to enhance their adaptive capacities and thus facilitate transformation?

I propose five principles that we can use to rethink planning as a paradigm for resilience and for transforming hybrid ecosystems:

1. *Complexity*: Create and maintain diverse development patterns that support diverse human and ecosystem functions.
2. *Resilience*: Focus on maintaining self-organization and increasing the capacity to adapt instead of aiming to control change and to reduce uncertainty.
3. *Uncertainty*: Expand the ability to consider uncertainty and surprise by designing strategies that incorporate uncertainties and are robust to the most divergent plausible futures.
4. *Adaptation*: Create options for learning through experimentation, and opportunities to adapt through flexible policies and strategies that mimic the diversity of environmental and human communities.
5. *Transformation*: Expand capacity for change through transformative learning by challenging assumptions and actively reconfiguring problems.