Chapter 10
Ecological Resilience as a Foundation for Urban Design and Sustainability

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Introduction

As humans have transformed themselves from a predominantly agrarian to urban species, the world has become increasingly planned and designed (Wu 2008a, b). Human domination has become the prevailing theme in society's interactions with nature for more than two centuries, particularly since the Industrial Revolution in the eighteenth century. With growing human dominance in the biosphere, nature has become increasingly "domesticated" (Kareiva et al. 2007). As Herbert Simon (1996) put it, "The world we live in today is much more a man-made, or artificial, world than it is a natural world."

Our increasingly managed and designed ecosystems and landscapes are met with an increasing number of problems, which can be summarized in one word – unsustainable. Cities now account for about 75% of the energy use, 60% of the residential water use, 80% of the wood used for industrial purposes, and 80% of the greenhouse gas emissions of the entire world (Grimm et al. 2008; Newman et al. 2009). The environmental problems associated with urbanization have been well recognized in both the fields of ecology and design. In a broad sense, the state of the world is a consequence of the faulty design activities of humanity. The statements by Van der Ryn and Cowan (1995) are incisive and far-reaching:

> In many ways, the environmental crisis is a design crisis. It is a consequence of how things are made, buildings are constructed, and landscapes are used. Design manifests culture, and culture rests firmly on the foundation of what we believe to be true about the world. Our

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> forms of agriculture, architecture, engineering, and industry are derived from design epistemologies incompatible with nature's own. It is clear that we have not given design a rich enough context. We have used design cleverly in the service of narrowly defined human interests but have neglected its relationship with our fellow creatures.

Indeed, landscape and urban designers and planners intentionally modify and create landscapes of different kinds for various human purposes, and their imprints and influences are profound and pervasive around the world. However, this fact and the quote by Van der Ryn and Cowan (1995) should not be interpreted as implying that landscape architects should be held responsible for the unsustainable cities and landscapes around us. We, as scientists, engineers, architects, and policy makers, all have participated in this domestication and design of ecosystems and landscapes on a range of spatial scales. As Herbert Simon (1996) has further articulated, "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones." Along the same line, Glaville (1999) argued that scientific research must be designed and thus is a design activity.

A myriad of factors are responsible for the current unsustainable state of the world. Two of them are particularly relevant to mention here: our inadequate or incorrect understanding of how nature works in science and our inadequate or misuse of ecological knowledge in action. Our perception of nature has often been shaped by myths and beliefs, such as the balance of nature, which has been an important background assumption in ecology (Botkin 1990; Pickett et al. 1992; Wu and Loucks 1992, 1995). Until recently, it was common to view biological populations, communities, and ecosystems as ordered systems that were kept at a constant stable equilibrium by homeostatic controls. This way of thinking may be attributed partly to the human tendency to seek order in everything, including nature (Wu and Loucks 1992, 1995). Also, confined by the balance of nature notion and the natural history tradition, mainstream ecology had long overlooked cities (Collins et al. 2000). Ecology and design did not seem compatible because almost everything that humans did to nature was perceived to be ecologically negative. For decades ecology was viewed as a "subversive science" because it was perceived as being the advocate of nature as against the actions of humans (Shepard and McKinley 1969; Kingsland 2005).

However, mounting evidence from ecological research in the past few decades indicates that nature is not in constant balance, but rather in eternal flux. This recent discovery has led to a fundamental transformation in ecological thinking from emphasizing equilibrium, homogeneity, and determinism to non-equilibrium, heterogeneity, and stochasticity – or a shift from the balance of nature/equilibrium paradigm to the hierarchical patch dynamics paradigm (Pickett et al. 1992; Wu and Loucks 1992, 1995). Wu and Loucks (1995) articulated five key elements of hierarchical patch dynamics: (1) ecological systems are spatially nested patch hierarchies, (2) dynamics of an ecological system can be studied as the composite dynamics of individual patches and their interactions, (3) pattern and process are scale dependent, (4) non-equilibrium and random processes are essential to ecosystem structure and function, and (5) ecological (meta)stability is often achieved through structural and functional redundancy and spatial and temporal incorporation of dynamic patches.

Only recently have these ideas of patch dynamics been applied in urban ecological studies (e.g., Pickett et al. 1997; Grimm et al. 2000; Zipperer et al. 2000; Wu and David 2002) and begun to find their way into urban design (McGrath et al. 2007).

In general, ecological principles have not been adequately incorporated in the theory and practice of design and engineering, and those principles that are applied tend to be outdated (Holling 1987; Pickett et al. 2004). Holling (1996) identified four such misunderstandings in design sciences: (1) changes in ecosystem structure and function are continuous and gradual, (2) ecosystems are spatially uniform and scale invariant, (3) ecosystems have a single equilibrium point, with stabilizing functions to keep them at this homeostatic state, and (4) policies and management practices based on such equilibrium-centered and "linear" thinking inevitably lead to applying fixed rules, looking for constant carrying capacity or constant sustainable yield, and ignoring scale dependence. To overcome these problems, resilience theory, an emerging body of ideas, principles, and knowledge for understanding, managing, and designing socio-ecological systems (Levin et al. 1998; Holling 2001; Walker and Salt 2006), can provide a comprehensive and powerful framework.

The objectives of this chapter, therefore, are to provide an overview of the essential elements of resilience theory, and then explore how it can guide the science and practice of urban design. We will elucidate the complex and adaptive properties of cities as socio-ecological systems, and examine why the agenda of urban sustainable development entails the adoption of resilience as a guiding principle.

Key Elements of Resilience Theory

The emerging theory of resilience, or resilience thinking, is based on several key concepts and ideas, including thresholds or tipping points, alternate stable states or regimes, regime shifts, complex adaptive systems, adaptive cycles, panarchy, and transformability (Holling 2001; Folke 2006; Walker and Salt 2006). In this section, we discuss how these concepts are defined and interpreted in the context of understanding and managing social-ecological systems.

What Is Resilience?

[AU3]

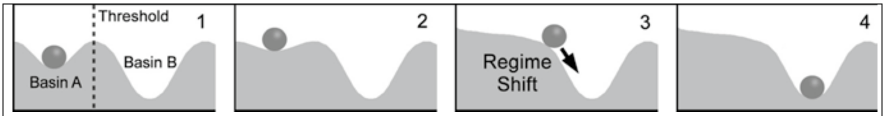
Engineering Resilience vs. Ecological Resilience

Resilience has been defined differently in ecology, with two contrasting connotations. Consistent with the classic ecological paradigm that presumes a single equilibrium state, the first connotation of resilience refers to the rapidity with which a system returns to its equilibrium after a disturbance, usually measured in time units (Innis 1975; Pimm 1984). In contrast, based on the observation that ecosystems often have multiple stable states, Holling (1973) defined resilience as the ability of a system to absorb change and disturbance without changing its basic structure and function or shifting into a qualitatively different state. The resilience concept based on multiple alternate states has been called "ecological resilience" or "ecosystem resilience," which stresses persistence, change, and unpredictability (Holling 1996). It differs from the classical equilibrium-centered resilience concept, termed "engineering resilience," which focuses on efficiency, constancy, and predictability (Holling 1996).

The modern discourse on resilience hinges on ecological, rather than engineering, resilience. More recent work has further expanded and elaborated Holling's (1973) original definition of ecosystem or ecological resilience. These revisions usually include the system's abilities to self-organize and adapt to changes, and also contributions that make resilience more pertinent to social and social-ecological systems (e.g., Holling 1996, 2001; Levin et al. 1998; Carpenter et al. 2001; Folke 2006). For example, social resilience is defined as the ability of a human community to withstand, and to recover from, external environmental, socioeconomic, and political shocks or perturbations (Adger 2000). The popularization of the term resilience across disparate fields seems to have made it increasingly removed from its original ecological meaning and more ambivalent in some cases (Brand and Jax 2007). Much of the recent research on resilience has been done in association with the Resilience Alliance, an international network of scientists, practitioners, universities, and government and non-government agencies, which was established in 1999 to promote resilience research in social-ecological systems (http://www.resalliance.org).

Multiple Stable States, Thresholds, and Regime Shifts

A critical assumption behind the concept of ecological resilience is the existence of multiple stable states, also known as basins of attraction, multiple equilibria, or regimes (Fig. 11.1). Thresholds – a concept similar to tipping points – refer to the boundaries between the basins of attraction, crossing which leads the system to a different regime. Such transitions of social-ecological systems between alternate stable states are known as "regime shifts" (Scheffer et al. 2001; Folke 2006). Regime shifts may result in abrupt and dramatic changes in system structure and function in some cases, or more continuous and gradual changes in other situations (Fig. 11.1). Examples of regime shifts are ubiquitous in environmental and human systems. For instance, a grassland may change to a shrubland due to overgrazing or climate change that pushes the system over a threshold in terms of vegetation cover and soil properties (Walker and Salt 2006). A productive lake with clear water can quickly become turbid upon reaching a tipping point from a steady influx of pollutants (Carpenter et al. 1999; Scheffer et al. 2000). Such dynamics illustrate the interplay of "slow" versus "fast" variables in the nonlinear dynamics of social-ecological systems. A slow moving attribute, such as a gradual stream of pollutants, can cause rapid shifts into a new state that is more visibly captured by the fast variable, such as lake nutrient concentration. Nonlinear dynamics, and regime shifts in particular, can result in a substantial element of surprise.



Real world examples:	Real world examples:	Real world examples:	Real world examples:
A healthy natural grassland ecosystem that is relatively resilient.	A degraded grassland due to overgrazing or prolonged droughts that is less resilient.	A grassland that is shifting into a desert-like system due to overgrazing or climate change.	A previous grassland has now become a shrubland or a desertified land.
A well-developed and managed city that is relatively resilient at present, but can shift into a different regime due to a disaster.	An urban system that has little resilience due to increasing environmental damage, social inequality, etc.	A city that is experiencing large-scale civil strife, escalating violence, hunger, or population crash.	An un-resilient city that has high poverty and crime rates and devastated natural environment, or a "ghost town."

Fig 11.1 Illustration of some key concepts of ecological resilience: multiple stable states, basins of attraction, threshold, and regime shift. Ecological and human systems often have alternate stable states (1 and 2), and change in resilience and regime shifts (3 and 4) may occur due to disturbances (Modified from Folke et al. 2004)

Specified and General Resilience

A system's resilience can also be discussed in terms of "specified resilience" (or "targeted resilience") and "general resilience" (Walker and Salt 2006; Walker and Pearson 2007). Specified resilience is the resilience "of what, to what," i.e., the resilience of a specified system response variable to a known disturbance (e.g., the resilience of human and ecosystem health to increased temperatures caused by urban heat islands). General resilience refers to the overall resilience of a system to withstand unforeseen disturbances, which does not specify any particular kind of shock or any particular system response variable. An example of this could be the overall capacity of a city to persist in a rapidly and unpredictably changing world. Walker and Salt (2006) have pointed out that specified resilience, although important, is not adequate alone, and that optimizing specified resilience may actually undermine the general resilience of a social-ecological system. This is mainly because too much focus on specified resilience tends to make the whole system less diverse, less flexible, and less responsive in terms of cross-sector actions (Walker and Salt 2006).

Complex Adaptive Systems

Recent developments in resilience research have emphatically recognized social-ecological systems as "Complex Adaptive Systems" (CAS). Insights from the study of CAS have been increasingly incorporated into the theory of resilience (Holling

2001; Walker and Salt 2006). While various definitions of CAS exist (Cowan et al. 1994; Holland 1995; Lansing 2003), the one by Levin (1999) has been widely used in the resilience literature: a complex adaptive system is “a system composed of a heterogeneous assemblage of types, in which structure and functioning emerge from the balance between the constant production of diversity, due to various forces, and the winnowing of that diversity through a selection process mediated by local interactions.”

Complex adaptive systems are characterized by self-organization, in which local interactions at small scales result in emergent patterns at larger scales. They are also characterized by adaptive processes, which typically produce multiple outcomes depending on accidents of history – a phenomenon known as “path dependence” (Kauffman 1993; Levin 1998, 1999). Levin (1998, 1999) has identified four key determinants that allow for self-organization to occur in CAS: heterogeneity, nonlinearity, hierarchical organization, and flows. Complex adaptive systems typically become organized hierarchically into structural arrangements through nonlinear interactions among heterogeneous components, and these structural arrangements determine (and are reinforced) by the flows of energy, materials and information among the components. Self-organization involves a never-ending process of the destruction of “old” constraints leading to the construction of “new” order, and this is not a goal preset from the top down but rather an inevitable consequence of local interactions expressing the collective influence from the bottom up (Levin 1998, 1999). Clearly, the characteristics of CAS cannot be explained by the traditional homeostatic equilibrium theory. Rather, their explanations necessarily invoke the ideas of ecological resilience, thresholds and criticality, multiple stable states, regime shifts or phase transitions, and hierarchy (Levin 1998, 1999; Wu 1999; Holling 2001; Wu and David 2002; Walker and Salt 2006).

Natural, human, and coupled natural-human systems are complex adaptive systems (Holland 1995; Levin 1998, 1999; Holling 2001; Lansing 2003). Brown (1994) discussed five characteristics of ecosystems that make them prototypical examples of CAS: (1) a large number of components, (2) open and far-from-thermodynamic-equilibrium, maintained through exchanges of energy, materials, and information with the environment, (3) adaptive, i.e., able to respond to changes behaviorally or genetically, (4) irreversible histories, and (5) capable of a variety of complex, nonlinear dynamics. While human systems have features similar to these, they also possess at least three unique characteristics: foresight and intentionality, communication capacities, and technological advances that influence every aspect of human society (Holling 2001). As socio-ecological systems, cities represent a quintessential example of complex adaptive systems, which are heterogeneous in space, dynamic in time, and integrative in function (Wu and David 2002).

Adaptive Cycles and Panarchy

From the theory of resilience, complex adaptive systems often exhibit recurring dynamics, moving through four phases: (1) an r phase of growth or exploitation, (2) a K phase of conservation or consolidation, (3) an Ω phase of release or collapse, and (4) an α phase of reorganization or renewal. These four phases are collectively known as the adaptive cycle, which is represented commonly by a ∞-shaped diagram (Holling 1986, 2001). While the r and K phases are two aspects of ecosystem dynamics that have long been studied in the context of ecological succession, the two additional phases were introduced into the adaptive cycle to highlight the importance of the interplay between growth and maintenance, between innovation and conservation, and between change and stability (Holling 1986, 2001).

Holling (1986) introduced the concept of the adaptive cycle with the example of ecosystem succession. After a disturbance an ecosystem starts recolonization and biomass accumulation with opportunistic and pioneer species (r-strategists) predominant in the early succession stage (r phase), and then gradually reaches maturity with locally competitive climax species (K-strategists) dominant in the late succession stage (K phase). During this process, biomass and nutrients accrue and become progressively more bound within the existing vegetation, and the ecosystem becomes increasingly more connected in structure, more rigid in regulatory control, and thus more brittle as a whole. Thus, a system in the K phase is characterized by high capital (or potential for other use), over-connectedness, and rigidity, representing a period of "an accident waiting to happen" (Holling 2001). For example, disturbances such as fires, storms, or pest outbreaks may trigger an abrupt collapse of the ecosystem, during which the tight regulatory control is broken up and the resources accumulated in the transition from r to K phases are released in the Ω phase. This sudden collapse, also known as "creative destruction" (sensu Schumpeter 1950), leads to an open and loosely organized situation with abundant opportunities, high uncertainties, and strong external influences. Resources are mobilized, and the ecosystem starts the process of reorganization (α). This leads back to the r phase, but there is no guarantee that the ecosystem will return to its previous state. As the adaptive cycle unfolds, system resilience expands and contracts: resilience is high in the α phase when potential (or capital) and connectedness (or controllability) are low, and low in the Ω phase when potential and connectedness are high.

Ecosystems that are unblemished by human encroachment adhere to a natural and salubrious cycle of growth and renewal. Dramatic events such as wildfires, while destructive, unleash the potential for revitalization and are a boon to the system's long-term health. Anthropogenic intrusions, however, can displace an ecosystem from its natural rhythm, resulting in collapses that are significantly more dramatic and potentially irreversible. In many parts of the United States, for instance, practices of fire suppression have disturbed naturally occurring fire regimes that are essential to the long-term health of forest ecosystems. Consequently, tree density and the accumulation of fuel loads now precipitate much more destructive fires that inflict long-term damage to both the ecosystem and adjacent communities (Covington 2000).

Human enterprises, from companies to nation states, exhibit similar cyclic dynamics, although not all systems move through the four phases in the same sequence discussed above – other transitions are possible (Walker and Salt 2006). The trajectory from r to K is called "the front loop" of the adaptive cycle, which is a long period of slow accumulation and transformation of resources with progressively higher predictability, whereas the trajectory from Ω to α is termed "the back

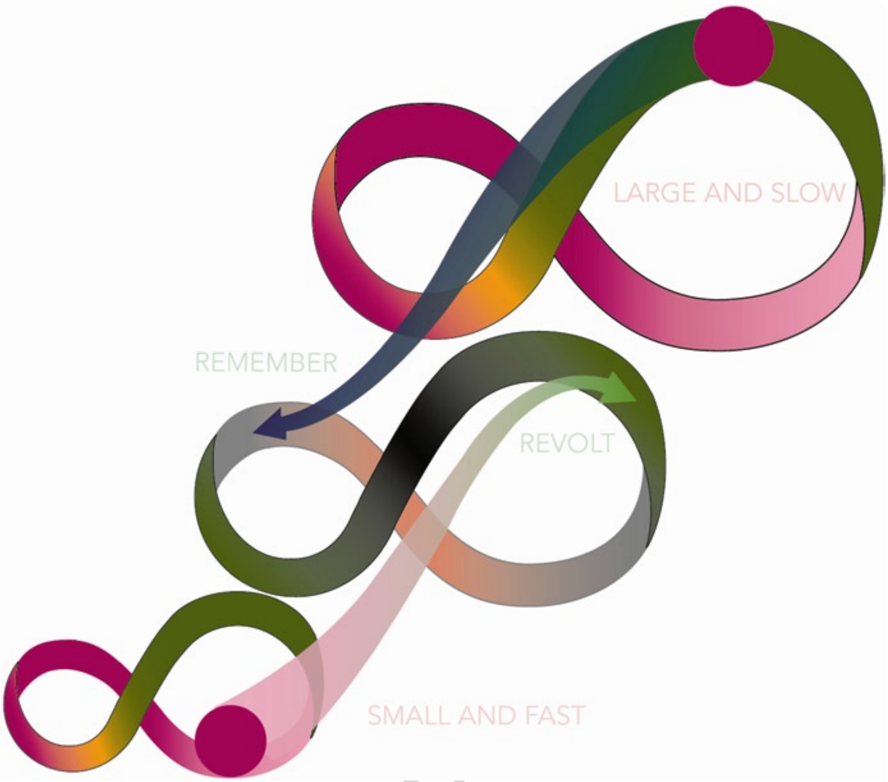


Fig 11.2 Illustration of panarchy as a hierarchy of adaptive cycles interconnected across different scales in time and space (Redrawn by Victoria Marshall based on Holling 2001)

loop", which is a short period of proliferation of opportunities and innovations with high uncertainties (Holling 2001).

Adaptive cycles occur over a wide range of spatial, temporal, and organizational scales, ranging from days to geologic epochs and from a leaf to the biosphere; the nested hierarchy of adaptive cycles arranged according to their characteristic scales is termed "panarchy" (Fig. 11.2; Holling 2001; Gunderson and Holling 2002). In other words, panarchy is "the hierarchical structure" in which natural, human, and social-ecological systems are "interlinked in never-ending adaptive cycles of growth, accumulation, restructuring, and renewal" across scales, describing "the evolving nature of complex adaptive systems" (Holling 2001). Holling (2001) further pointed out that in a healthy social-ecological system, "each level is allowed to operate at its own pace, protected from above by slower, larger levels but invigorated from below by faster, smaller cycles of innovation." That is, slower moving processes operating at higher levels and faster moving processes at lower levels act in "remember" and "revolt" functions for the scale of focus (Holling 2001; Walker and Salt 2006). For instance, in a forest, an initial fire originating at local level can quickly expand to consume large stretches of the system – "revolt." Correspondingly, after the conflagration has abated, the forest can renew itself by drawing upon resources such as seed banks and returning organisms from broader scales – "remember."

Panarchy integrates the concepts of thresholds, multiple stable states, regime shifts, complex adaptive systems, and hierarchy theory together to explain the dynamics of social-ecological systems, and has become a central piece of resilience theory (Gunderson 2000; Holling 2001; Gunderson and Holling 2002; Walker and Salt 2006).

Resilience and Sustainability

From a resilience perspective, sustainability is not about maintaining a system at its equilibrium state by reducing the variability in system dynamics or optimizing a system's performance, but rather sustainability should focus on the system's capacity to create and test opportunities and maintain adaptive capabilities (Holling 2001). Thus, resilience is the key to the sustainability in social-ecological systems (Walker and Salt 2006). This shift from a perspective oriented around stability, optimality and predictability to a perspective focusing on inherent uncertainty is in favor of a "risk management" approach to sustainability – avoiding potentially catastrophic regime shifts. Adaptability is promoted by self-organization. Preserving the ability to self-organize in the face of disturbances is a crucial characteristic of resilient systems. Thus, we may argue that all sustainable systems must be resilient, but not necessarily always stable. Indeed, in the face of social and environmental disturbances – from changing climatic conditions to geopolitical struggles, destructive hurricanes to armed conflicts – the ability to self-organize and preserve system integrity is crucial to realizing long-term sustainable development.

From a panarchical perspective, sustainability is inherently a multiple-scale concept. To achieve sustainability is not to get stuck in the conservation phase within an adaptive cycle, but rather to maintain proper operations of all four phases within each cycle as well as harmonic linkages between adjacent cycles across scales in space, time, and organization. Through a panarchical analysis, we may identify breaking points at which a social-ecological system are more brittle and leverage points at which positive changes are most effective for fostering resilience and sustainability (Holling 2000). As the expanding scale of human enterprise generates more and more coupled socio-ecological systems on a range of scales, we expect that the resilience perspective will play an increasingly important role in the science and practice of sustainability.

Resilience Thinking of Urban Design and Urban Sustainability

Cities are quintessential examples of complex adaptive systems. As discussed in the previous sections, ecological resilience is the key to the sustainability of such systems. Several attempts have been made to apply the concept of resilience to urban systems in recent years (Pickett et al. 2004; Vale and Campanella 2005; Wallace and Wallace 2008). For example, Alberti et al. (2003) discussed urban resilience as "cities—the degree to which cities tolerate alteration before reorganizing around a new set of structures and processes." Pickett et al. (2004) articulated the use of ecological (rather than engineering) resilience as a powerful metaphor for bridging ecology with urban planning. Vale and Campanella (2005) defined urban resilience as the capacity of a city to rebound from a disaster, which is an engineering resilience perspective as per Gunderson (2010).

Applying the theory of ecological resilience in urban design can result in design principles that are quite different from the traditional ones that emphasize stability, optimality, and efficiency. In this section, we explore several aspects of resilience thinking in the context of urban design and urban sustainability. These are neither specific guidelines nor actionable recipes for urban design, but rather are pointers that are useful for developing such guidelines and recipes for designing resilient cities.

Cities as Panarchies

Key to understanding the behavior of cities as complex adaptive systems is to study the interactions between spatial patterns and ecological and socioeconomic processes operating at differing temporal, spatial, and organizational scales. Thus, it is useful to think of cities as panarchies with nested adaptive cycles of characteristic scales in space and time. In an urban environment, panarchical dynamics, as illustrated through the example of fire in a forest ecosystem, also take place. For instance, a protest originally confined to a single neighborhood or locality may gain momentum and spread to other parts of the city, eventually evolving into a large-scale constructive reform or destructive revolt. The case of constructive reform is often indicative of a resilient political system that encourages healthy democratic participation and local feedbacks. The case of revolt may be due to a lack of social resilience, as law enforcement and the broader infrastructure fail to temper the contagion of uprising activities. Once the revolt has dissipated, administrators can rely on the social capital of the local community and the financial and political support from higher levels of government to clean up the resultant messes and help with reconstruction efforts.

Urban development is driven by a myriad of processes, facilitated by various institutions, and operating at different levels. Although there is no single blueprint that can adequately capture the relevant systemic attributes of all cities, every urban region is necessarily confronted with social, environmental, and economic challenges. Dealing with any single issue in isolation is not sufficient to address the resilience of the city as a whole. Focusing on proximate causes is rarely a sustainable solution, as processes operating both above and below galvanize and constrain the dynamics at hand. Ameliorating urban poverty, for instance, is not simply a matter of "pumping more money" into impoverished neighborhoods. Underlying this phenomenon can be factors at lower levels such as poor educational standards and cultural stigmas, as well as constraints from higher scales, such as poor governance and deteriorating urban infrastructure.

The cross-scale dynamics of urban systems can induce phenomena that are truly difficult to predict. As urban regions expand in size, density, and composition, they are increasingly subject to this complexity of socioeconomic and biophysical forces. The financial crisis of 2008 and 2009, termed the "Great Recession" by many economists, is a salient example of catastrophic collapse occurring in a system with low resilience. While the Great Recession was a worldwide phenomenon, the American "housing bubble" of the early 2000's is a major culprit for the severity of the collapse. Land use regulation significantly effects the pattern of real estate development (Pendall et al. 2006), and the disparity of regulatory policy may explain the differences in how severely the recession has impacted different cities. The roles played by regulation and the housing market, and consequences to urban areas in the wake of a major economic perturbation, are representative of panarchical, cross-scale dynamics. The recession operating at the scale of the entire country and the world is exacerbated by the collapse of housing bubbles of urban regions. The deepening financial crisis then feeds back to impact real estate prices and constrain economic activity at the lower scale of cities.

Climate change presents one of the greatest challenges to urban sustainability, which has cross-scale implications. With urban populations swelling, cities will continue to be the primary contributors of greenhouse gases to the atmosphere. As the planet warms, urban regions will then have to adapt to the consequences of the human-altered climate system, such as rising sea levels and higher occurrences of hurricanes. As we saw with the Asian Tsunami of 2004 and Hurricane Katrina of 2005, the effects of natural disturbances on heavily populated regions can be devastating. Thus, as the effects of urbanization continue to motivate biophysical changes at the global scale, resultant consequences of altered climatic conditions will feed back to create novel environmental conditions to which cities must inevitably adapt (Newman et al. 2009).

Connectedness, Modularity, and Tight Feedbacks

Resilient social-ecological systems usually have high diversity and individuality of components, local interactions, and an autonomous process that selects certain components for replication or enhancement based on the outcomes of the local interactions (Levin 1998, 1999; Holling 2001). Hierarchical or modular structure can facilitate all these three important features of complex adaptive systems. This has immediate implications for urban design. Cities can become more spatially homogenous when urbanized areas expand and coalesce. Correspondingly, a higher connectivity of the urban land cover can decrease modularity, resulting in more rapid distribution of the effects of a disturbance. Decision-making processes that drive social development may also become increasingly insulated from natural environmental conditions – a phenomenon that has repeated itself numerous times in human history (Redman 1999). The confluence of factors that weaken the "pillars" of system robustness lowers the resilience of urban systems to perturbations, be they environmental (e.g., natural disasters) or social (e.g., riots). To foster urban resilience and sustainability, therefore, "designing patch dynamics" can serve as a tool to maintain proper levels of diversity, variability, and flexibility in cities. Designing patch dynamics is not only relevant but also critically important for bringing the insights of ecology into urban design and planning (McGrath et al. 2007; Pickett and Cadenasso 2007; Wu 2008a).

The loosening of short-term feedback loops between social and ecological variables eventually leads to long-term problems for urban development. Urbanization predicated on immediate objectives, such as profit maximization from development without proper attention to social and ecological consequences in the distant future, will compromise the potential for urban resilience and sustainability. Cooperative interactions can be enhanced by greater spatial propinquity and repeated interactions over time (Levin 2006). Social isolation can create a sense of narrow individualism, and lead to behaviors that are injurious to community and environment. Fostering greater "social capital" through institutions and programs is important to promoting effective organization (Dasgupta and Serageldin 2001), especially at the scale of urban settings.

Accounting for Nature's Services in Cities

As humanity becomes an increasingly urban enterprise, it is important to consider cities as socio-ecological systems, supported by ecosystem services. Ecosystem services refer to the benefits that humans derive from the natural environment, including provisioning services such as food and water; regulating services such as regulation of floods, drought, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits (Millenium Ecosystem Assessment 2005). The economic and social wellbeing of a society is inextricably tied to the availability of these ecosystem services or "natural capital." Urban development, however, can result in a significant loss of ecosystem services and thus a decrease in the city's cross-scale resilience.

Many urban ecosystem services are well-known to planners and city dwellers at large. Urban forests, for example, contribute numerous services such as air quality control and real estate appreciation (McPherson 1992; Wu 2008a, b). With regard to the pressing challenges of climate change, urban carbon sequestration is a service of great significance. While the importance of "natural" ecosystems such as forests and grasslands are well noted, there is less focus on the role of urban ecosystems in this regard. Recent studies have shown that urbanization of cities in arid environments can increase net primary production substantially (Buyantuyev and Wu 2009). This has significant implications for carbon sequestration capacity at a region scale. Another important way in which urban "nature" contributes to a city's wellbeing is in the form of "cultural services." Urban greenspaces, such as open and park-like spaces, are a hallmark of modern cities, offering a sense of place and opportunities for recreation. These spaces should be integrated into the urban context, and form a mainstay of social interactions and a diverse repository of species and other natural elements. These services should be considered in any sustainable design agenda (Chen and Wu 2009). To build resilient cities, urban designers and planners should properly account for nature's services to a city by investing in its natural capital (cf. Spirn, Chap. 6, this volume).

Combining Specified Resilience with General Resilience

Specified resilience may be designed and built into cities to target well-known threats and vulnerabilities. For example, cities located along coasts where hurricanes and tsunamis occur with relatively high frequency may gear their infrastructural improvements toward mitigating the impact of such occurrences. Similarly, major financial and political centers that are considered likely targets to potential terrorist disturbances may develop security protocols to hedge these dangers. Indeed, designing for specified resilience is in large part a historical exercise – developing mitigation or adaptation strategies from observation and experience. This can be fruitfully accomplished where evidence is plentiful and identified disturbances are tractable to prediction. The "planetary boundaries" of several key earth-system processes, including climate change, nitrogen and phosphorous cycles, rate of biodiversity loss, land use change, global freshwater use, stratospheric ozone depletion, and ocean acidification, have been identified recently, and crossing such boundaries can lead to disastrous consequences for humanity (Rockström et al. 2009). These boundaries not only help delineate a safe "operating space" for humanity at the global scale, but should also guide urban design and decision-making at the scale of cities.

In a world beset by consistent novelty in the form of unforeseen social and biophysical changes, urban regions also need to develop general resilience to a broad range of expected and unexpected, known and unknown disturbances. Ultimately, only "generally resilient" cities are sustainable in an uncertain world. An adaptive management approach provides a robust framework for urban design that promotes general resilience. Inherent in the theory of resilience and adaptive management is the role of uncertainty and surprise (Carpenter et al. 2009). New emergent pandemics such as the H1N1 flu strain, sudden climatic shifts, and other abrupt perturbations are often refractory to prevailing monitoring capacities. In facing uncertain challenges, the most basic recourse is stoking the capacities for adaptation and self-organization to retain the same identity (Holling 2001; Folke 2006). This requires maintaining the demographic, economic, and ecological integrity of a city and developing robust governance structures that underlie self-organizing and adaptive potentials. The consequences of failing to design for resilience is tragically illustrated by the impact of Hurricane Katrina on the American Gulf Coast, specifically the city of New Orleans, in August, 2005. In that instance, a large natural disturbance, combined with a poor governance structure, resulted in a catastrophic collapse of social wellbeing. Applying the institutional analysis as advocated by Ostrom (2009) in urban environments can help develop sustainable governance of shared resources such as transportation and sanitation systems, and further our understanding of how urban design can foster adaptive capacity.

Developing Capacities for Urban Transformability

It is crucial to note that there can also be a negative dimension of having high resilience. A system can sometimes become resilient in a less desirable regime. For instance, urban regions besieged by impoverishment may be stuck in "poverty traps," where a suite of socioeconomic factors have induced a highly robust state of squalor. Low levels of education, endemism of substance abuse, and poor quality of governance can generate a series of tight feedback loops that prove immensely difficult to be overcome. The same genre of dynamics can also affect rural regions, urban fringes, and other socio-ecological systems, manifesting in environmental degradation and the depletion of valuable ecosystem services. This is the case in many urban areas of the developing world, and illustrates that resilience can work as both a vehicle of sustainability and an agent of destitution. In such situations, the primary motivation of understanding resilience and employing adaptive strategies is reversed – sustainable development then means finding ways of overcoming the robustness of undesirable regimes.

The capacity to overcome the obstacles of an undesirable regime to create a fundamentally new system is called transformability (Walker et al. 2004; Folke 2006; Walker and Salt 2006). Configuring an entirely new system means introducing new state variables – the attributes and processes that determine the qualitative character of the system. For instance, when dealing with deep urban poverty traps of high robustness, "urban renewal" may call upon the obsolescence of the underlying social, political, or economic determinants of the current condition. Social pathologies such as rampant drug use or a fundamentally flawed educational system may underpin the squalor at hand, perpetuating vicious cycles of impoverishment and disenfranchisement. In this case, it may become necessary to overhaul the administrative and incentive structure of the city's school districts, crack down on a multinational drug-based economy, and introduce rehabilitative opportunities to promote more productive activities.

Concluding Remarks

The world is dynamic, and change is ubiquitous. Cities, as prototypical complex adaptive systems, are not only dynamic but also self-organizing and actively adjusting to cope with change. These changes include a myriad of disturbances, some of which are known and predictable, but most of which are unforeseen and unpredictable. Urban design can play a critically important role in the self-organization and adaptive progression of cities. How urban design affects urban sustainability, however, depends heavily on design principles that are increasingly influenced by ecological theory. We have discussed that the traditional equilibrium paradigm in ecology presumes homogeneity, predictability, and inherent stability of ecosystems, suggesting that the focus of sustaining a system should be on keeping it at stasis. In sharp contrast, the hierarchical patch dynamics paradigm explicitly recognizes heterogeneity, nonlinearity, and multiple stable states, suggesting "flux of nature" and "order out of disorder" (Pickett et al. 1992; Wu and Loucks 1992, 1995). The ideas of heterogeneity, non-linearity, hierarchy, and multiple stable states are also essential in the theory of ecological resilience, which has emerged as a major approach to understanding and managing social-ecological systems, including urban design. This theory suggests that, to design sustainable cities, our emphasis should be on creating and maintaining urban resilience – the ability of a city to persist without qualitative change in structure and function in spite of disturbances. Pickett et al. (2004) have argued that "cities of resilience" can be a powerful metaphor for drawing together insights from both ecology and planning.

What would a resilient city look like? We do not believe that there is a universal model. Nevertheless, we believe that the features of "a resilient world," as envisioned by Walker and Salt (2006), may provide some clues:

1. Diversity: Promoting diversity in all its dimensions, from biological to economic, and encourage multiple components and resource uses to balance and complement homogenizing trends.
2. Ecological variability: Seeking to understand and work with the boundaries of the inherent variability of ecological and socio-ecological systems; attempting to tame such variability is often a recipe for disaster.
3. Modularity: Maintaining modularity can help hedge against dangers of low resilience caused by over-connectedness in system structure and function.
4. Acknowledging slow variables: Managing for resilience means understanding the "slow" or controlling variables that underpin the condition of a system, especially in relation to thresholds. By recognizing the importance of these critical variables, we can better avoid shifts to undesirable stable states and possibly enhance the capacity of a desirable regime to deal with disturbances.
5. Tight feedbacks: Tightening or maintaining the strength of feedback loops allows us to better detect thresholds. The weakening of feedback loops can result in an asymmetry between our actions and the consequences stemming from them. Salient examples of such dynamics include pollution and overconsumption.
6. Social capital: Promoting trust, social networks, and leadership to enhance the adaptive capacity for better dealing with the effects of disturbance.
7. Innovation: Embracing change through learning, experimentation, and promoting locally developed rules. Instead of narrowing our range of activities and opportunities, we should be seeking to explore and cultivate new ones.
8. Overlap in governance: Developing institutional arrangements that manage for cross-scale influences. Developing "redundancy" and overlap in governance frameworks enhances response diversity and flexibility.

9. Ecosystem services: Recognizing and accounting for ecosystem services when managing and designing for resilience. The benefits society derives from nature are regularly underpriced and ignored. Such services are often lost as socio-ecological systems shift into different, less desirable regimes.

At the heart of the resilience perspective on urban design is its focus on change instead of stasis – "to withstand change with adaptive change," not to deal with change by resisting or diminishing change. This is in the same spirit of "progress" as defined by Herbert Spencer (1857) – change underlies progress, which is "a beneficent necessity." Resilience theory suggests that what underlies a truly resilient city is not how stable it has appeared or how many little disturbances it has absorbed, but whether it can withstand an unforeseen shock that would fundamentally alter or erase the city's identity. For modern cities to be truly sustainable, therefore, urban design must explicitly account for the influence of both internal and external changes. Only by viewing urban regions as complex socio-ecological systems with feedback loops, cross-scale interactions, and inherent uncertainties can we design resilient cities. We argue that in applying the key ideas and principles of resilience, it is important to think of the seemingly opposing processes, such as change vs. stability, creativity vs. conservation, and flexibility vs. efficiency, not as paradoxes but dialectical duals that must coexist to achieve a synthesis of urban resilience.

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