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Insight, part of a Special Feature on Managing Surprises in Complex Systems

Ecological and Human Community Resilience in Response to Natural Disasters

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ABSTRACT. Ecological resilience, adaptive cycles, and panarchy are all concepts that have been developed to explain abrupt and often surprising changes in complex socio-ecological systems that are prone to disturbances. These types of changes involve qualitative and quantitative alterations in systems' structures and processes. This paper uses the concepts of ecological resilience, adaptive cycles, and panarchies to compare ecological and human community systems. At least five important findings emerge from this comparison. 1) Both systems demonstrate the multiple meanings of resilience—both in terms of recovery time from disturbances and the capacity to absorb them. 2) Both systems recognize the role of diversity in contributing to resilience. 3) The comparison highlights the role of different forms of capital and 4) the importance of cross-scale interactions. 5) The comparison reveals the need for experimentation and learning to build adaptive capacities. All of these ideas have broad implications for attempting to manage complex systems with human and ecological components in the face of recurring natural disasters.

Key Words: *ecological resilience; surprises; urban recovery*

INTRODUCTION

On the morning of August 29, 2005, Hurricane Katrina moved inland from the Gulf of Mexico and quickly moved over the city of New Orleans. The storm surge, rainfall, and winds resulted in massive flooding and the loss of life and property. The hurricane also reminded us that human attempts to control nature often result in failure. In the case of Katrina, that control took the form of a complex levee and canal system that was designed to withstand the flooding of the Mississippi River and the surrounding lowlands. The storm surge of Hurricane Katrina raised water levels in the sound east of the city, causing levees to fail and subsequent flooding to occur in the city.

The flood damaged the components of the coupled social-ecological system at a variety of spatial and temporal scales. Fifty levee breaches were recorded, and much of the levee system needs to be rebuilt. Homes and other municipal infrastructures were destroyed by the flood, with losses estimated to be over 50 billion U.S. dollars (Kates et al. 2006). More than 1,500 lives were lost, and some (estimates of up to one-third) of the population of the city has moved away following the storm. While some portions of the system were irreversibly changed, other portions have recovered at different rates (Kates et al. 2006). Just as temporal scales of recovery are variable, so are the spatial scales of impacts and recovery. At the smallest scale, vegetation patches are recovering, as are some individual homes. Neighborhoods, especially the downtown business districts, have bounced back, as have components of regional energy production. However, the U.S. federal government, which takes a leading role in disaster relief, was seen as slow and incompetent in reacting to the disaster.

This natural disaster reveals many of the problems, issues, and challenges facing planners and managers who attempt to understand and manage disasters in human communities (Pelling 2003, Scheffer et al. 2003, Adger et al. 2005, Barthel 2005, Elmqvist et al. 2003, Janssen et al. 2006). From a systems perspective, many natural disasters can be viewed as perturbations or disturbances to a human community system. The speed, severity, and complexity of natural disasters continually challenge the ability of society to generate appropriate responses. Kates et al. (2006) suggest

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that planning for such disturbances may involve trade-offs between adapting to short-term, common events and larger, perhaps costlier disturbances that occur over a longer time horizon. While managers can anticipate some of the types of impacts that are associated with different disturbances, many of these impacts cannot be known, foreseen, or predicted. Hence, appropriate responses must include anticipating unexpected never-before-experienced effects and impacts (Holling 1978, Walker and Salt 2006). In addition, it is important to understand how previous actions and extant structures may contribute to increased and unforeseen vulnerabilities (Holling 2001, Kates et al. 2006).

One premise of this article is that human communities and ecosystems can be characterized using a systems perspective. That is, both of them are systems in the sense of being comprised of structures and processes at specific spatial-temporal scale ranges. System boundaries are defined in urban systems on the scales of neighborhoods, towns, counties, or metropolitan areas (Alberti and Marzluff 2004, Elmqvist et al. 2004, Barthel et al. 2005) showing similar nesting of ecological structures, such as patches, stands, forests and biomes (Holling 2001). The components within these boundaries interact and change in simple and complex ways at specific scales (Brand 1994), but they are also subject to external processes or perturbations. Due to the nature of these cross-scale interactions, they are viewed as being complex adaptive systems. Complex adaptive systems are not easily analyzed or understood, but rather characterized by emergent properties, self-organization, historical patterns of abrupt, non-linear change, and unpredictable dynamics (Costanza et al. 1993, Holling 2001, Liu et al. 2007). By conceptualizing human communities and ecosystems as complex adaptive systems, systemic properties such as resilience or adaptive capacity can be compared. The extent of the similarities and differences between these systems is explored in this article.

The remainder of this article is divided into four sections. The first section describes how resilience is perceived and understood in ecological and human communities. The second section describes how factors such as diversity and capital can increase or decrease a system's resilience. The third section examines cross-scale interactions in terms of disturbances, resilience and panarchy. The final section presents some insights on how adaptive capacity is developed through anticipation and learning.

CONTRASTING ECOLOGICAL AND COMMUNITY RESILIENCE

Resilience can be traced to the Latin word *resalire*, which translates as "walking or leaping back" (Skeat 1882). As such, in many different disciplines it denotes the capacity to rebound or recover after a shock or an event. Some scholars use the term to describe the amount of time needed to recover following an external force or perturbation. Ecological resilience was first used by Holling (1973) to describe two different aspects of change in an ecosystem over time. His first characteristic of resilience involved the persistence of relationships within a system and the "ability of systems to absorb changes of state variables, driving variables and parameters, and still persist" (Holling 1973). The second defining characteristic described resilience as "the size of a stability domain or the amount of disturbance a system could take before it shifted into an alternative configuration" (Holling 1973). These two views of resilience are not incompatible, the major difference between them is whether the system of interest returns to a prior state or reconfigures into something very different.

Ecologists who work in disturbance-driven ecosystems find that ecological resilience is a more applicable concept to the complex changes they observe. These scientists observe qualitative changes in both the structure and function of ecosystems (Gunderson 2000, Scheffer and Carpenter 2003, Folke et al. 2004) or the ecological regime or identity (Walker et al. 2006, Walker and Salt 2006). Walker (1981) and Dublin et al. (1990) found dramatic shifts between grass-dominated and shrub-dominated ecosystems in semi-arid rangelands that were mediated by interactions between herbivores, fires, and drought cycles. Scheffer and Carpenter (2003) described two alternative states (clear water with rooted aquatic vegetation and turbid water with phytoplankton) in shallow lake systems. Gunderson (2001) described shifts in wetland vegetation as a result of changes in nutrient status and disturbances such as fires, drought, or frost. Coral reef system shifts between coral domination and macro-algae domination have also been reported (Hughes 1994, Nystrom and Folke 2001, Bellwood et al. 2004), and many hypothesis have been offered to explain this phase transition, including overfishing, the population decline of key grazing species, increases in nutrients, and shifts in recruitment patterns (Hughes et al. 2003). Estes and Duggin (1995) and Steneck et al. (2004) have shown how near-shore temperate marine systems shift between being dominated by kelp and sea urchins as a function of the density of sea otters and other grazers.

Vale and Campanella (2006) define urban resilience as "the capacity of a city to rebound from destruction", which is similar to Holling's (1996) definition of engineering resilience. Yet, other authors apply ecological resilience concepts to community or urban resilience (Wallace and Wallace 2008). Urban resilience involves a regime change in which the structures, processes and identity of a community either evolve into a more-desired configuration or devolve into a less-desirable state. Examples of the former include the transformation of San Francisco into a "modern city" following the earthquake of 1906 (Vale and Campanella 2005) or the decline of New Orleans as a regional center of culture and economic and political power following the 1927 flood of the Mississippi River (Barry 1997).

VULNERABILITIES: FACTORS THAT INFLUENCE RESILIENCE

Ecological resilience can be eroded by a number of mechanisms. One of the earliest observations (Holling 1986) was that practices that stabilize or homogenize key elements of a system erode resilience. A common example is the suppression of forest fires in fire-adapted systems. The longer fires are excluded from these systems, the more fuel accumulates. The amount of fuel and spatial distribution increases the likelihood of a more intense fire that could lead to a regime shift (Holling 1986). This occurred in the mid-1990s in central Florida, as human community development occurred in fire-adapted pine forests. As houses were constructed in previous decades, many homeowners allowed trees and shrubs to grow in their yards and surrounding areas. When fires started during dry periods in the 1990s, the higher fuel loads led to an increase in the fire damage, and many homes were destroyed.

Another way in which ecological resilience is eroded is through changing pathways of biogeochemical cycles. The Everglades nutrient level described above is one such example. Algal blooms and vegetation shifts in shallow freshwater lakes (Carpenter 2003, Scheffer and Carpenter 2003, Scheffer et al. 2001) are another example. Many inland waters, such as the Baltic Sea (Troell et al. 2005), have undergone regime shifts because of nutrient introductions.

The loss of ecological resilience and the ensuing regime changes can be due to a shift in key controlling processes (Holling 1973, Wallace 2008). Nutrients are one form of control in ecosystems, as suggested above. Regime shifts have been documented in aquatic systems as a result of changes in trophic relationships. Coral reefs (Hughes et al. 2003, 2005), kelp forest ecosystems (Estes and Duggin 1995, Steneck et al. 2004), and freshwater lakes (Carpenter 2003) have all undergone regime shifts as a result of the overharvesting of key species. Are there analogous situations in human communities to those of trophic cascades observed in ecological systems in communities? The parallel situation in human communities would entail the removal of key functional roles during or after a disaster that would lead to different and undesirable outcomes. Perhaps the loss of law-enforcement personnel in areas immediately after a disaster leading to anarchy is such an example. Another example is a post-disturbance collapse of economic systems that results in temporary barter systems until formal economic relationships recover.

Diversity

The role of diversity in an ecological system's response to disturbances has been studied and debated for over three decades. Indeed, a growing body of experimental evidence reveals how biotic diversity can stabilize ecosystems that are subject to perturbations (Tilman et al. 1996). Biological diversity refers to both the different types of species and the different functional roles of species. Tilman et al. (2001) demonstrated that more diversity helped in the recovery of ecosystem functions (productivity, biogeochemical cycling) after a disturbance. This finding is very similar to Berke and Campanella's (2006) observation that a diverse economy can contribute to human community resilience (capacity to rebound following destruction). These studies refer to an engineering form of resilience (or stability) because of the theory that diversity helps a system more quickly return to its pre-disturbance conditions.

For three decades, other ecologists have explored the relationship between biological diversity and resilience (Peterson et al. 1998). Aspects of biodiversity (especially functional redundancy) have a positive influence on ecological resilience (Walker et al. 1999, Peterson et al. 1998, Allen et al. 2005). For example, overgrazing in rangelands selectively removes drought-resistant species. When droughts subsequently occur, the system suddenly flips into a shrub-dominated ecosystem. Elmqvist et al. (2003) demonstrated similar linkages between response diversity and resilience in a range of ecological systems. Elmqvist et al. (2004) argue that spatial forms of functional diversity (land use types) build resilience in human community landscapes.

Over time, systems develop and adapt by buffering the impact to recurring disturbances. Buffering in this sense refers to the moderation (lessening) of impacts from disturbance. By moderating disturbances, the system can be very resilient. In water management systems, levees and canals provide buffers against floodwaters (at least to their designed extent). Two other examples of buffering can be found in coastal ecosystems. In the state of Florida, governmental policies protect coastal mangrove forests from development. These forests provide buffers against storm surges (Berke and Campanella 2006), as demonstrated in south Florida in 1992, when Hurricane Andrew severely impacted coastal mangrove forests; these forests took the brunt of the wind and wave energy, thereby sparing the inland areas. Others argue that the protection of barrier islands is critical for similar reasons (Pielkey and Fraser 2003). Following Hurricane Katrina, Day et al. (2007) demonstrated how management that led to the loss of coastal wetlands in Louisiana increased the vulnerability of the area to hurricane impacts.

CROSS SCALE PROCESSES OF RENEWAL AND RECOVERY

Processes that interact across spatial and temporal scales influence both ecological and community system recoveries. The temporal dimensions for recovery occur over distinct eras, and cover timescales ranging from days to decades. In ecological systems, Nystrom and Folke (2001) demonstrated how processes at different spatial scales were critical to coral reef recovery following hurricanes. An equivalent model can be found in how state, federal, and international governments come to the aid of local communities following disasters (Adger et al. 2005). This applies not only for the short-term timeframe when basic human necessities of water and food are imported to the affected areas from larger spatial domains but also for how they act over longer periods of time. Houck (1985) and Klein and Zellmer (2006) discuss how federal policies of flood protection, flood insurance, and regulatory regimes can help in the recovery from floods yet can also make communities more vulnerable to future flood events. How these processes play out over temporal and spatial scales is one of the key factors in the resilience of a system, whether it is an urban community or an ecosystem.

Holling (1986) labels a post-disturbance period of renewal and recovery as the alpha phase. This is the period immediately following a disturbance or creative destruction. It is the phase that is most vulnerable to random and chance events. This is also the phase in which many opportunities emerge for alternative system configurations. Olsen et al. (2006) describe this as a "window of opportunity, in which new actions and arrangements are possible." One of the differences between ecological and community systems is that human-dominated systems contain members that can conceptualize and look forward to the future (Westley et al. 2002, Scheffer et al. 2003, Redman and Kinzig 2003), whereas ecological systems do not have this ability. As a result, communities develop alternative plans for recovery and renewal that allow the system to develop in a new and different trajectory (Berke and Campanella 2006). This process is similar to Gunderson et al.'s (1995) view of policy renewal following ecological crises.

Both the ecological and community resilience literature recognize the importance of the post-disturbance phase of the system to the subsequent trajectory or regime (Holling 2001, Vale and Campanella 2005, Masten and Obradovic 2007). This is, in essence, one of the distinctions that Holling (1973, 1996) makes between engineering and ecological resilience. The ensuing trajectories or regimes have some components that are similar, but in many cases following large disturbances, the system undergoes a transformation or change in its identity (Cumming et al. 2005). Vale and Campanella (2005) discuss how the city of San

Francisco, for example, transformed following the earthquake of 1906 into a modern, more progressive city with more efficiency, discipline, and order as compared to the city that existed prior to the disaster. In other words, the disaster provided the opportunity for the city to become a great city. Barry (1997) described a similar transformation (but in the opposite direction) in New Orleans; following the flood of 1927, the city was not the central economic, political, and social seat of power in the southern United States that it was prior to the flood.

Different forms of capital are critical to post-disturbance recovery in both types of systems. These include natural capital (Folke et al. 2002) and social capital (Putnam 2000) as well as other economically defined forms of capital. Natural capital in this sense refers to the stocks (or goods) in ecosystems that provide service or use to humanity. One example is the release of organic matter from coastal vegetation associated with hurricanes. Hurricane-force winds defoliate trees, and storm surges and tides dislodge organic soils. As a result, estuaries and coastal systems receive large inputs of organic matter, which in turn fuels a post-disturbance pulse in the estuarine production of shrimp, fish, and other organisms (Day et al. 2007).

One important way in which capital is developed and applied is through different types of networks in both ecological and social systems. Janssen et al. (2006) provide a useful typology of networks in the context of resilience: those that facilitate the flow of resources and ideas and those that facilitate connections among people. The loss of resilience in marine systems has been attributed to the loss of key linkages within a trophic network (Estes and Duggins 1995, Hughes et al. 2003, 2005). Formal and informal social networks can also aid in post-disaster recovery. Tidball and Krasny (2007) found that community activities, such as the development of urban gardens and the creation of green space, foster resilience through the development of social networks. Nelson et al. (2007) present examples of how social networks can contribute to more effective management during drastic variations in key environmental drivers, such as droughts. Longstaff and Yang (2008) indicate the role of trust and communication in building resilience within social networks.

Post-disturbance recovery is determined, in part, by remnant components, or the types and forms of capital that were not destroyed by a disturbance. Berke and Campanella (2006) refers to these aspects of the system as "sticky" aspects (not removed by disturbances) that include physical infrastructure (such as underground utilities and foundations) and social or legal relationships that do not change (such as land ownership or allegiance to a place). Analogous components in ecological systems would include remnant rootstocks that survive fires or seed banks in wetland systems. Indeed, many fire-adapted plant species only regenerate after fires because the fire triggers the release of seeds. Adaptations to recovery in ecological systems can be found across a range of scales and levels of organization, including the individual, species, population, and ecosystem levels.

BUILDING ADAPTIVE CAPACITY THROUGH ANTICIPATION AND LEARNING

There is no evidence that ecological systems can anticipate disturbances or disasters. There is no ability among these assemblages to recognize or conceptualize such events or manage them as human communities can. The components of ecological communities can adapt to recurring disasters, but this is done through the mechanisms of selective pressure. For example, many pine trees produce bark that is resistant to fires as a result of selective pressures over millennia. Anticipation is also referred to as the human capacity for foresight and intentionality (Holling 2001). However, the inherent unpredictability of disasters (and other ecological dynamics) can limit the ability of humans to anticipate complex dynamics (Carpenter et al. 1999). Regardless, human communities find ways to anticipate and plan for disasters.

There are at least two components making up the ability of communities to anticipate natural disasters. One is the predictive capacity of knowing when and where a disaster might occur, and the second is anticipating the impact of those disasters on communities. Both of these components generally rely on past experience or the history of natural disasters.

During the 20th century, a tremendous amount of technology was developed to increase our ability to predict the occurrence of natural disasters. Many governmental agencies collected and analyzed information regarding when and where natural disasters might occur. These programs provided different types of information over different time and space scales. These programs also developed and applied multiple methods or techniques of anticipation. Take, for example, the activities of the U.S. National Hurricane Center (NHC) to predict hurricanes. The NHC has a historical record of hurricanes in the Atlantic basin going back over a hundred years. Those data have been used to develop long-term (multi-decadal) and broad-scale (regional) patterns of hurricane occurrences. One such pattern is the probability of the landfall of a hurricane for segments of the eastern coastline from Texas to Maine. Gray and his colleagues (Gray et al. 1992, Blake and Gray 2004) also published seasonal and monthly predictions of tropical cyclones in major ocean basins. At even finer scales, the NHC coordinates weekly and daily forecasts using a suite of computer models combined with forecasters' understandings and experiences. In spite of this daunting array of tools and experience, there are still great uncertainties about when and where disasters will occur.

The second component of the anticipation of natural disasters is the capacity to foresee the impacts of these events. This is a much more difficult task, and often it is only learned by experiencing repeated disasters because understanding is built through experience. One reason for this difficulty is the inherent unpredictability of complex systems that arises from synergies, nonlinearities, and cross-scale interactions (Holling and Gunderson 2002). Kates and Clark (1996) make a similar distinction between surprises resulting from events and those resulting from the consequences of events.

In managed ecosystems, the loss of resilience and sudden alteration in an ecosystem's state is often viewed as a surprise (Holling 1986, Gunderson 2003). An ecological surprise is defined as a qualitative disagreement between ecosystem behavior and human expectations about that behavior (Gunderson 2003). Brooks (1986) provides a useful typology of surprises in describing the interaction between technology and society, and defines three types of surprises: (a) unexpected discrete events, (b) discontinuities in long-term trends, and (c) the emergence of new information. Gunderson (2003) and Nelson et al. (2007) discuss similar categories in resource systems as local surprises, cross-scale surprises, and true novelties. Natural disasters, such as hurricanes, tornadoes, and tsunamis, can be local surprises if there is no prediction or warning of their occurrences. Cross-scale surprises refer to situations in which resilience is lost and a disturbance or natural disaster suddenly causes reorganization into a new configuration. The floods of 1927 and Hurricane Katrina could be considered cross-scale surprises to the city of New Orleans. These categories are relevant because they provide examples of different activities in terms of how people anticipate and manage the unknown (Kates and Clark 1996).

The preceding section highlighted the difficulties of prediction and management in complex systems (Holling 1978, Walters 1997, Kates and Clark 1996). Effective planning and management, however, require some estimation of "what will happen." Certainly, broad information about what will happen is generally known. For example, it was well-known at least three days prior to the landfall that Hurricane Katrina was going to strike the Gulf Coast of the United States (with a given probability), yet all of the impacts could not be specifically predetermined. While there are many sources of complexity, and limits to predictability, it is clear that successful management for resilience must include a learning-based approach that allows for the accumulation and periodic testing of knowledge (Gunderson 2001, Gunderson and Holling 2002).

Learning

Forms of social learning occur following natural disasters and other ecological events. That learning is forced when the failure of an extant policy is undeniable (Gunderson et al. 1995). One type of learning emerging from these events is episodic learning, when previous models or schemes are no longer tenable because of a single event or crisis (such as the faith in levees to control flood waters prior to Hurricane Katrina). Episodic learning involves the creation of new policies or approaches to solve the problems that were revealed by an ecological event. Ongoing planning, experimentation, and management can lead to episodic learning, as has occurred in the Great Barrier Reef and Grand Canyon resource systems over the past decade (Hughes et al. 2007). Transformational learning is characterized by cross-scale surprise and/or the emergence of novel solutions. In these cases, learning involves solving problems in identified problem domains among sets of difficult and complex variables (Westley 2002). Another type of learning, called transformational learning, involves several levels in a panarchy rather than only one level (Holling and Gunderson 2002, Gunderson et al. 2006). The development of the Everglades restoration is one example of transformational learning. In that case, a number of problem domains (ecological, social, and economic) were solved by viewing restoration as a win-win solution for all sectors rather than as a zero-sum game of conflict for water control among the agricultural, urban, and conservation sectors (Gunderson and Light 2006). In both forms of learning, an environmental event or natural disaster can create a "window of opportunity" for collective action in socio-ecological systems (Olsson et al. 2004, 2006) as well as human community systems (Berke and Campanella 2006).

SUMMARY

A number of resilience concepts have been applied to both ecological and human communities (Table 1). Scholars of both ecological and community resilience recognize that at least two different types of resilience exist. Some ecologists focus on the time of recovery in ecosystems (Tilman et al. 2002) as a metric of resilience, while social scholars (Kates et al. 2006) discuss similar metrics in the recovery of human systems. Both ecologists and social scientists also recognize the ecological form of resilience and the presence of alternative regimes. Just as ecosystems undergo phase shifts from one type to another, so can neighborhoods, towns, and cities.

Diversity is important in providing ecological resilience. Numeric diversity (different types of entities) is probably less important than functional diversity is (Walker and Salt 2006). In addition, the ways in which functional units are connected is a critical factor in contributing to system resilience (Berke and Campanella 2006).

Various forms of capital are critical to ecological and community resilience. Capital is developed during phases of system growth and development. That capital, as well as the influx of capital from broader areas, is critical for system recovery and determining a system's trajectories (MEA 2005). Especially important to natural disasters is the role of maintaining or restoring natural capital in the form of ecosystem goods and services (Liu et al. 2007, Olshansky and Kartez 1998). Wetland ecosystems-whether forested or not-are critical buffers for mitigating the impacts of hurricanes in coastal areas (Day et al. 2007). Floodplain ecosystems provide similar functions during extreme floods.

Coupled systems of humans and nature are complex in terms of how they anticipate and respond to natural disasters. These complexities present great uncertainties for many facets of society. The capacity to deal with the types of uncertainties and surprises will require novel approaches, creative combinations of strategies, and the ability to adapt to a changing environment. Accelerating learning and supporting novel approaches that limit vulnerability and expand our understanding of the occurrence and impacts of natural disasters seem to be critical components of building community resilience.

Responses to this article can be read online at:
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