

1

Resilience of Large-Scale Resource Systems

Lance H. Gunderson, C. S. Holling,
Lowell Pritchard Jr., and Garry D. Peterson

Regional-scale systems of people and nature provide some of the most vexing challenges for attaining social goals of sustainability, biological conservation, or economic development. There are many more examples of failures than successes, as measured by numerous resource systems that exist in a constant or recurring state of crisis (Ludwig et al. 1993). In the Florida Everglades, agricultural interests, environmentalists, and urban residents contest with one another for control over clean water (Light et al. 1995). In the Pacific Northwest region of the United States, various advocates of salmon argue over the appropriate use of the Columbia River with those who prefer cheap hydroelectric power (Lee 1993; Volkman and McConnaha 1993). The nations surrounding the Baltic Sea struggle with issues of governance as the fish populations and water quality of the sea declines (Jansson and Velner 1995). Within Zimbabwe, large-scale land use conversions are testing stabilities of both ecological and political structures. In these cases resource management has taken a pathological form in which the complexity of the issues, institutional inertia, and uncertainty lead to a state of institutional gridlock, when inaction causes ecological issues to be ignored and existing policies and relationships to be continued.

Paradoxically, this failure often arises from the success of initial management actions. Managers of natural resource systems are often successful at rapidly achieving a set of narrowly defined goals. Unfortunately, this success encourages people to build up a dependence upon its continuation while simultaneously eroding away the ecological support that it requires. This leads to a state in which ecological change is increasingly undesirable to the people dependent

upon the natural resource and simultaneously more difficult to avoid. This management pathology leads to unwanted changes in nature, a loss of ecological resilience, conservative management policies, and loss of trust in management agencies.

Recent work reveals a way out of this pathology in large, regional-scale systems. These systems move through periods of surprise, crisis, and reformation (Gunderson et al. 1995). Managers are surprised when the inadequacies of many, if not most, management policies are revealed by ecosystem dynamics. A crisis occurs when it becomes unambiguously clear that existing policies caused this surprise. The crisis is followed by periods of denial, resistance, and often, finally, by a period of reformation during which new policies are developed and implemented. It is during these periods of crisis that institutions and the connections between them are most open to dramatic transformation. This ability to transform and survive requires that the resource system have sufficient resilience to permit the experimental development of new management policies.

What Is Resilience?

Resilience has been defined in two different ways in the ecological literature, each reflecting different aspects of stability. One definition focuses on efficiency and depends on constancy and predictability—all attributes of engineers' desire for fail-safe design. The other focuses on persistence, despite change and unpredictability—all attributes embraced and celebrated by evolutionary biologists and by resource managers who search for safe-fail designs. Holling (1973) first emphasized these contrasting aspects of stability to draw attention to the tensions between efficiency and persistence, between constancy and change, and between predictability and unpredictability.

The more common definition, which we term *engineering resilience* (Holling 1996), conceives ecological systems to exist close to a stable steady state. Engineering resilience, then, is the speed of return to the steady state following a perturbation (Pimm 1984; O'Neill et al. 1986; Tilman and Downing 1994). This idea of disturbance away from and return to a stable state is also at the center of twentieth-century economic theory (Varian 1992; Kamien and Schwartz 1991).

The second definition, which we term *ecological resilience* (Walker et al. 1981; Holling 1996), emphasizes conditions far from any stable steady state, where instabilities can shift or flip a system into another regime of behavior—in other words, to another stability domain (Holling 1973). In this case, resilience is measured by the magnitude of disturbance that can be absorbed before the system is restructured with different controlling variables and processes.

The differences between these two aspects of stability—essentially between a

focus on maintaining efficiency of function (engineering resilience) and a focus on maintaining existence of function (ecological resilience)—are so fundamental that they can become alternative paradigms in which subscribers dwell on received wisdom rather than the reality of nature. Those using the concept of engineering resilience tend to explore system behavior near a known stable state, while those examining ecological resilience tend to search for alternative stable states and the properties of the boundaries between states.

Those who explore engineering resilience and the near-equilibrium behavior of ecosystems operate in the primarily deductive tradition of mathematical theory (e.g., Pimm 1984) that imagines simplified, untouched ecological systems; or they draw upon the traditions of engineering, which are motivated by the need to design systems with a single operating objective (Waide and Webster 1976; DeAngelis 1980; O'Neill et al. 1986). These approaches simplify the mathematics and accommodate the engineer's drive to develop optimal designs. However, there is an implicit assumption that ecosystems exhibit only one equilibrium steady state or, if other operating states exist, that those states should be avoided (figure 1.1).

On the other hand, those who emphasize ecological resilience come from

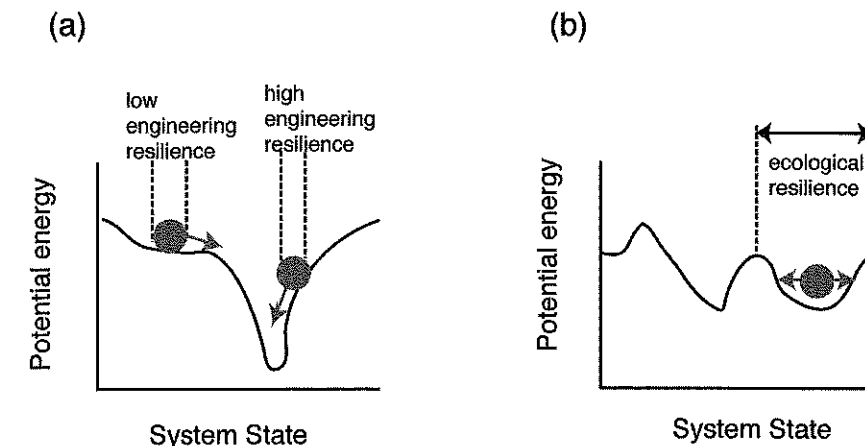


Figure 1.1. Stability landscapes can be used to represent the dynamics of a system and alternative definitions of resilience. The ball represents the system "state." The state can be changed by disturbances, which move the system along a stability landscape. The shape of the landscape is determined by controlling variables of the system. Engineering resilience (speed of recovery) is a local measure and is determined by the slope of the landscape. (a) Depressions in the landscape with low slopes have less engineering resilience than areas that have steep slopes. (b) Ecological resilience of a system corresponds to the width of a stability basin.

traditions of applied mathematics and applied resource ecology at the scale of ecosystems—for example, of the dynamics and management of freshwater systems (Fiering 1982), of forests (Holling et al. 1977), of fisheries (Walters 1986), of semi-arid grasslands (Walker et al. 1981) and of interacting populations in nature (Sinclair et al. 1990; Dublin et al. 1990). Because these researchers are rooted in inductive rather than deductive theory formation, and because they have experience with the impacts of large-scale management actions, they believe that it is the variability of critical variables that forms and maintains the stability landscape. When this variability is reduced, an ecosystem can flip from one organization to another (figure 1.1).

In economics, there has also been a focus on single stable state. The history of economics has been to rapidly move from establishing the existence of a general equilibrium to examining issues of equilibrium uniqueness, stability, and comparative statics. If multiple equilibria are shown to theoretically exist, then the challenge is to theoretically reduce the salience of alternate stable states by proposing that expectations, norms, and social institutions make some equilibria unlikely. This approach does not examine or explain the conditions that can cause a system to move from one stability domain to another. Recently, however, the identification of multi-stable states due to path dependence (Arthur et al. 1987), chreodonic development (Clark and Juma 1987), and non-convexities such as increasing returns to scale (David 1985) has reintroduced multiple stable states to economics.

The existence, or at least the importance, of multiple or single stable states determines the appropriateness of an engineering or ecological approach to resilience. If it is assumed that only one stable state exists or can be designed to exist, then the only possible definition and measures for resilience are near-equilibrium ones—such as characteristic return time. And that is certainly consistent with the engineer's desire to make things work—and not to intentionally make things that break down or suddenly shift their behavior. But nature and human society are different.

Why Study Resilience?

Complex resource systems are organized from the interactions of a set of ecological, social, and economic systems across a range of scales. Resilience is central to understanding the dynamics of these systems and their vulnerability to various shocks and disruptions. Resilience measures the strength of mutual reinforcement between processes, incorporating both the ability of a system to persist despite disruptions and the ability to regenerate and maintain existing organization. Resilience allows a system to withstand the failure of management

actions. Management is necessarily based upon incomplete understanding, and therefore ecological resilience allows people in resource systems the opportunity to learn and change.

The importance of the role of resilience in ecosystems, flexibility of institutions, and incentives in economies emerged in a sequence of meetings held on the island of Askö in the Swedish archipelago. Sponsored by the Beijer International Institute for Ecological Economics, these meetings brought together economists and natural scientists to explore similarities and differences in views and experiences of change. Their conclusions were that economic growth is not inherently good, nor inherently bad, but that economic growth cannot in the long term compensate for declines in environmental quality. They also concluded that the growing scale of human activities is encountering the limits of nature to sustain that expansion (Folke and Berkes 1998; Arrow et al. 1995).

The familiar responses to these issues are often flawed, because the theories of change underlying them are inadequate. The stereotypical economist might say “get the prices right” (i.e., ensure that prices internalize significant environmental externalities) without recognizing that price systems require a stable context where social and ecosystem processes behave “nicely” in a mathematical sense (i.e., are continuous and convex). The stereotypical social scientist might say “get the institutions right” without comprehending the degree to which those institutions submerge ecological uncertainties and economic and political interests. The stereotypical ecologist might say “get the indicators right” without recognizing the surprises that nature and people inexorably and continuously generate. And the stereotypical engineer might say “get the technological control right and we can eliminate those surprises” without recognizing the limits to knowledge and control imposed by the inherent uncertainty and unpredictability of the ever-evolving interaction of people and nature.

Although based on bad or insufficient theory, such simple prescriptions are attractive because they seem to replace inherent uncertainty with the spurious certitude of ideology, of precise numbers or of action. The theories implicit in these examples ignore multi-stable states. They ignore the possibility that the slow erosion of key controlling processes can cause an ecosystem or economy to abruptly flip into a different state that might effectively be irreversible. In an ecosystem, this might be caused by the gradual loss of a species in a keystone set that together determine structure and behavior over specific ranges of scale. In a resource-based economy, it might be implementation of maximum sustained yield policies that reduce spatial diversity, evolve ever-narrower economic dependencies, and develop more rigid organizations. In an economy, it might be caused by the channeling of loans through personal networks, allowing bad loans

to accumulate to such a point that they cause an entire banking and finance system to collapse—such as the Asian financial crisis in the late 1990s.

It increasingly appears that effective and sustainable development of technology, institutions, economies, and ecosystems requires ways to deal not only with near equilibrium efficiency but also with the reality of more than one possible equilibrium. If there are multiple equilibria, in which direction should the finger on the invisible hand of Adam Smith point? If there is more than one objective function, where does the engineer search for optimal designs? In such a context, a near-equilibrium approach is myopic. Attention should shift to determining the constructive role of instability in maintaining diversity and persistence and to management designs that maintain ecosystem function despite unexpected disturbances. Such designs maintain or expand the ecological resilience of those ecological “services” that invisibly provide the foundations for sustaining economic activity and human society.

The goal of this volume is to begin to understand how the properties of ecological resilience and human adaptability interact in complex, large systems (regional scale). To lay a foundation for this volume, we initially review other key properties of complex adaptive systems that contribute to resilience.

Properties of Complex Adaptive Systems

We propose that the behavior of complex adaptive systems depends upon four key properties: ecological resilience, complexity, self-organization, and order. As discussed above, resilience is the extent to which a system can withstand disruption before shifting into another state. Complexity is the variety of structures and processes that occur within a system. Self-organization is the ability of these structures and processes to mutually interact to reinforce and sustain each other. The process of self-organization produces order from disorder, but the interaction of processes across scales also destroys, and reconfigures, ecological organization, producing complex ecological dynamics. The next three sections elaborate upon the role these properties play in complex systems, and how these other properties contribute and interact with resilience.

Diversity and Stability

The relationship between biological diversity and ecological stability has been an ongoing debate in ecology since the time of Darwin (1860; also Elton 1958; May 1973; Tilman and Downing 1994, 1996). The question is whether an ecosystem that includes more species is more stable than one that includes fewer species?

Tilman and Downing (1994) and Tilman (1996) demonstrated that an increase in species number increases the efficiency and stability of some ecosystem functions but decreases the stability of the populations of the species, at least over ecologically brief periods. Although this work is important and interesting, it focuses only on the behavior of ecosystems near some steady state. But, as we’ve discussed above, we feel it is important to discover the role of ecological diversity over a much broader range of variations. This is where the relationship between diversity and resilience has been poorly developed.

When grappling with this broader relationship between diversity and resilience, most turn to two commonly discussed hypotheses: Ehrlich’s (1991) *rivet hypothesis* and Walker’s (1992) *driver and passengers hypothesis*. The rivet hypothesis proposes that there is little change in ecosystem function as species are added or lost, until a threshold is reached. At that threshold the addition or removal of a single species leads to system reorganization (just as popping rivets from a seam causes little change at first, but at some point sudden, disastrous change will occur). The rivet hypothesis assumes that species have overlapping roles and that as species are lost the ecological resilience of the system is decreased, and then overcome entirely. Walker proposes that species can be divided into *functional groups*, or *guilds*, which are groups of species that act in an ecologically similar way. Walker proposes that these groups can be divided into “drivers” and “passengers.” Drivers are “keystone” species that control the future of an ecosystem, while the passengers live in but do not significantly alter their ecosystem. However, as conditions change, endogenously or exogenously, species shift roles. Removing passengers has little effect, while removing drivers can have a large impact. Ecological resilience resides both in the diversity of the drivers and in the number of passengers who are potential drivers. These two hypotheses provide a start, but richer models of ecological complexity are needed that better incorporate ecological processes, dynamics, and scale.

Ecosystems are resilient when ecological interactions reinforce one another and dampen disruptions. Such situations may arise due to compensation when a species with an ecological function similar to another species increases in abundance as the other declines (Holling 1996) or as one species reduces the impact of a disruption on other species.

Theory, models, and data suggest that a small number of keystone processes create discontinuous spatial and temporal patterns in ecosystems (Holling et al. 1996; Levin 1995) yet allow for great diversity of organisms. Such keystone ecological processes produce a discontinuous distribution of structures in ecosystems, and these discontinuous structures generate discontinuous patterns in adult body masses of animals that inhabit landscapes (Holling 1992; Morton 1990; Allen et al. 1999). Consequently, while animals that function at the same

scale are separated by functional specialization (e.g., insectivores, herbivores, arboreal frugivores, etc.), animals that function at different scales can utilize similar resources (e.g., shrews and anteaters are both insectivores but utilize insects at different scales). We propose that the resilience of ecological processes, and therefore of the ecosystems they maintain, depends upon the distribution of functional groups within and across scales (Peterson et al. 1998).

Across-scale resilience is produced by the replication of process at different scales. The apparent redundancy of similar functions replicated at different scales adds resilience to an ecosystem. Because most disturbances occur at specific scales, similar functions that operate at other scales are maintained.

Local processes such as competitive relationships certainly contribute to species differences among ecosystems. However, the structural differences among ecosystems from the tundra to the tropics are primarily produced by larger-scale disturbance processes that are initiated locally and then spread across landscapes. These contagious processes include abiotic processes, such as fire, storms, and floods, and zootic processes, such as insect outbreaks, large mammal herbivory, and habitat modification (Naiman 1988; McNaughton 1988; Pastor and Cohen 1996). These processes, interacting with topography and regional climate, form the ecosystem-specific structures that shape the morphology and diversity of animal communities. They also generate spatial and temporal variation that increases the diversity of plant species by periodically overriding the competitive dominance relations that occur locally (Holling 1991). For example, in the eastern boreal forest of Canada, fire and spruce-budworm outbreaks kill large areas of forest. Through interactions with climate, existing vegetation, and each other, these processes produce a mosaic of even-aged forest stands in the landscape. Since the age a stand reaches before being destroyed is primarily determined by disturbance, and what species exist within the stand is influenced by landscape pattern, these disturbance processes also strongly control what exists within stands. Consequently, these disturbance processes strongly influence the distribution and type of resources that occur in eastern Canadian boreal forest across a broad range of ecological scales.

An ecosystem that has several scales of ecological structure allows members of multi-taxa food guilds to minimize competition by utilizing resources that are available at different scales (figure 1.2). The replication of function across scales can be seen on Brazil's Maracá Island Ecological Reserve, where palm seeds are dispersed across a range of scales by a variety of species (Fragoso 1997). Seed dispersers range in size from small rodents, which typically disperse seeds within 5 meters of parent trees, to tapirs (*Tayassu tajacu*), which disperse seeds as far away as 2 kilometers. Seed dispersal at multiple scales allows the palm population to

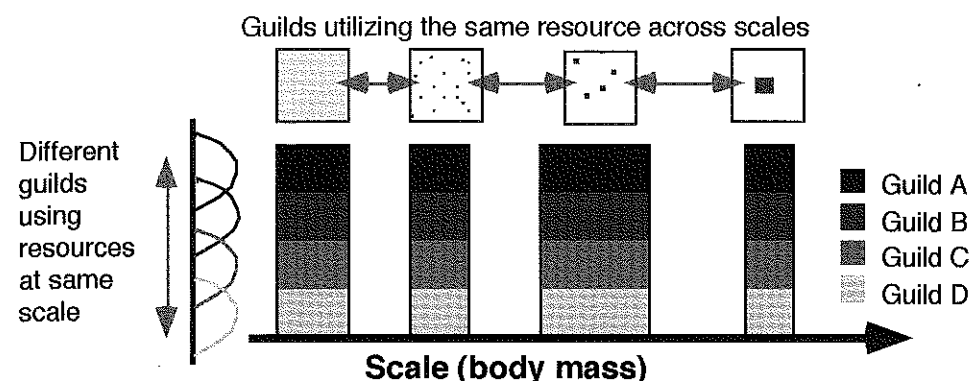


Figure 1.2. Animal species belonging to different ecological guilds exist at different body sizes. For example, there are both small and large insectivores. This distribution provides two forms of resilience. At the same scale animals from different guilds can utilize the same resources with lower efficiency. Also, animals that utilize the same resources can begin to utilize resources from a lower level if they form large enough aggregations. For example, if insectivores were removed from a group, insects would become easier to catch, making it worthwhile for animals at the same scale to switch from their normal food to insects, and it may become worthwhile for larger insectivores to eat prey items they normally would not eat.

persist despite a variety of disturbance processes occurring at different scales, because the trees are dispersed across the landscape at different scales.

Within-scale resilience complements cross-scale resilience. Within-scale resilience is produced by compensating overlap of ecological function between similar processes that occur at the same scales. For example, when a range of food resources is exploited by a set of foragers, rapid response to sudden increases or decreases in one type of food becomes possible and introduces strong negative feedback regulation over a wide range of densities of the food items (Holling 1987). The consequence of all that variety is that the species combine to form an overlapping set of reinforcing influences that are less like the redundancy of engineered devices and more like portfolio diversity strategies of investors. The risks and benefits are spread widely to retain overall consistency in performance independent of wide fluctuations in the individual species. Functional diversity provides great robustness to the functioning of the process and, as a consequence, provides great resilience to the system behavior. Moreover, this seems to be the way many biological processes are regulated: overlapping influences by multiple processes each one of which is inefficient in its individual effect but together operating in a robust manner. For example, such multiple-mechanism features control body temperature regulation in

endotherms, depth perception in animals with binocular vision, and direction in bird migration.

Because of the ecological resilience produced by functional diversity and the nonlinear way behavior suddenly flips from one ecological organization to another, gradual loss of species involved in maintaining ecological organization initially may have little immediate impact. But, as the loss of species continues, different behavior will emerge more and more frequently in an increasing number of places. To the observer, it would appear as if only the few remaining species were critical when in fact all contribute to ecosystem resilience. Although behavior would change suddenly, resilience measured as the size of stability domains (*sensu* Holling 1973) would gradually contract. The system, in gradually losing resilience, would become increasingly vulnerable to perturbations that earlier could be absorbed without change in function, pattern, and control.

Cross-Scale Dynamics

In nature, different structures and processes dominate at different scales. For example, in the boreal forest, fresh needles cycle yearly, the crown of foliage cycles with a decadal period, and trees, gaps, and stands all cycle at periods close to a century in length and even longer. Ecological organization can be viewed as a hierarchy in which each hierarchical level has its own distinct spatial and temporal attributes. A critical feature of such hierarchies is the asymmetric interactions that occur between levels (Allen and Starr 1982; O'Neill et al. 1986). In particular, the larger, slower levels constrain the behavior of faster levels; that is, slower levels control faster ones. However, if that were the only asymmetry, then hierarchies would be static structures and it would be impossible for organisms to exert control over slower environmental variables. In fact, these hierarchies are not static but are transitory structures maintained by interaction across scales.

Birth, growth, death, and renewal cycles (figure 1.3) transform hierarchies from fixed static structures to dynamic adaptive entities whose levels are sensitive to small disturbances at the transition from growth to collapse (the omega phase) and at the transition from reorganization to rapid growth (the alpha phase). During other times, the processes are stable and resilient. They constrain lower levels and are immune to the buzz of noise from small and faster processes. It is at the two phase transitions between gradual and rapid change that the large and slow entities become sensitive to change from the small and fast ones.

When the system is reaching the limits to its conservative growth, it becomes increasingly brittle and its accumulated capital is ready to fuel rapid structural changes. The system is very stable, but that stability derives from a web of interacting connections. When this tightly connected system is disrupted, the dis-

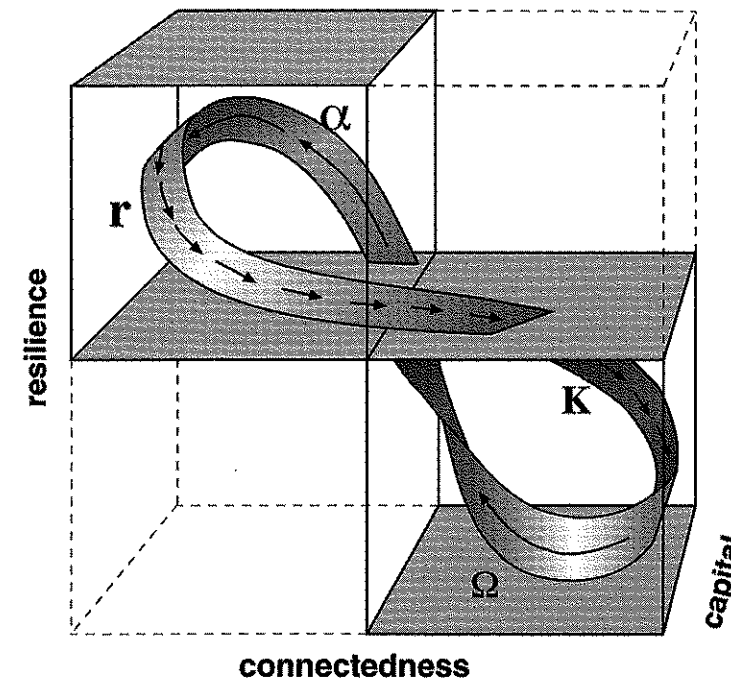


Figure 1.3. Ecosystem dynamics, indicating transitions among stages (r , K , Ω , α) and the resilience of each stage. The arrows show the speed of that flow in the cycle, arrows close to each other indicate a rapidly changing situation and arrows far from each other indicate a slowly changing situation. The cycle reflects changes in three attributes: x -axis, the degree of connectedness among variables, y -axis, the resilience of the system (low to high), and z -axis, the amount of accumulated capital (nutrients, carbon) stored in variables that are the dominant structuring variables at that moment in the system.

ruption can spread quickly, destabilizing the entire system. The specific nature and timing of the collapse-initiating disturbance determines, within some bounds, the future trajectory of the system. Therefore, this brittle state presents the opportunity for a change at a small scale to cascade rapidly through a system and bring about its rapid transformation. This is the “revolt of the slave variable” (Diener and Poston 1984). Such a collapse can be initiated by either internal conditions (e.g., the amplification of internal oscillations) or external events (e.g., the amplification of an external disturbance). Internally induced brittleness (linked to overconnected and accumulated capital) provides the conditions for an externally triggered collapse.

The second opportunity for small-scale processes to cause system change is

during the transition from reorganization to exploitation, that is, from alpha to r . During this reorganization phase, the system is in a state opposite to that of the conservation phase previously described. There is little local regulation and stability, so the system can easily be moved from one state to another. Resources for growth are present, but they are disconnected from the processes that facilitate and control growth. In such a weakly connected state, a small-scale change can nucleate a structure amidst a sea of chaos. This new structure can then use the available resources to grow explosively and to establish the exploitative path along which the system develops. As in Waddington's chreodonic development model, there is not a stable point; rather, there is a stable trajectory that progressively reinforces itself (Hodgson 1993). In Waddington's (1969) words, "the system is not homeostatic (around a point), it is homeorhetic (around a path)." This transition occurs as small-scale changes sow seeds of order in the larger and slower chaos within which they are embedded. The budworm example illustrates these changes where transient bottom-up asymmetry provides an opening for evolutionary change. That is, the previous system pattern may reassert itself, or the system may reorganize itself into a novel structure.

As systems go through phases of the adaptive cycle, resilience changes. This is presented as a third dimension in figure 1.3. When the system is reaching the limits to its conservative growth (K phase), it becomes increasingly brittle and its accumulated capital is ready to fuel rapid structural changes. The system is very stable, but that stability is self-maintaining and brittle, leaving the system vulnerable to novelty. A small disturbance can push it out of that stable domain into catastrophe; hence, its resilience is relatively low. The nature and timing of the collapse-initiating disturbance determines, within limits defined by the nature of lower and higher hierarchical levels, the future trajectory of the system. During reorganization (alpha phase) a system has greater resilience but little stability. Fluctuations in large-scale processes, such as climate, or in small-scale processes, such as a seed bank, can result in a system establishing different organizations.

Panarchy

The accumulating body of evidence from studies of ecosystems indicates that processes and structures often are discontinuous, and ecosystems can exhibit multiple stable states. The four-phase cycle of adaptive renewal captures many of these dynamics for ecological systems (figure 1.3). However, that model is appropriate for structures within a specific range of scales, and those dynamics occur at multiple hierarchical scales or levels. By considering the dynamics of

adaptive cycles interacting across scale, we have developed a model of cross-scale ecological organization that we call *panarchy*.

Panarchy describes the dynamic nature of interacting hierarchies. We prefer this term over *hierarchy*, because it emphasizes the dynamic and transient nature of connections between scales. Different systems exhibit the birth, growth, death, and renewal phases of the adaptive cycle at different specific scale ranges (figure 1.3). As in a conventional hierarchy, the processes within a level are stable and self-maintaining, constraining smaller and faster processes while benign and immune to their fast fluctuations. However, the panarchy model transforms hierarchies from fixed static structures to dynamic adaptive entities whose levels are sensitive to small disturbances at the transition from growth to collapse (the omega phase) and during the transition from reorganization to rapid growth (the alpha phase). It emphasizes that the "creative destruction" that follows "revolt" and the "remembrance" that shapes reorganization are the products of cross-scale interactions (figure 1.4).

Tests of resilience are from the "revolt" event. Revolts are enabled by the interaction across scales of slow and fast variables. Resilience shrinks as slow

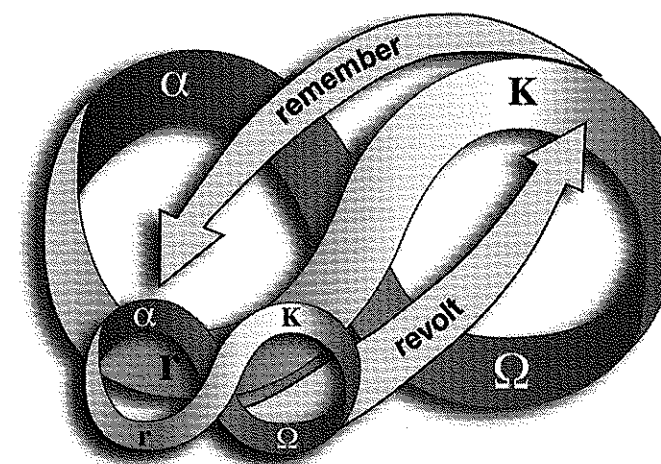


Figure 1.4. Sample of panarchical interactions showing two structural elements (such as a pine needle, represented by the smaller cycle, and tree crown, represented by the larger cycle). For each element, the four system phases (r , K , Ω , α) are as described in figure 1.3. Arrows labeled "revolt" and "remember" indicate key linkages across space and time scales. Smaller-scale elements that are in the Ω phase (creative destruction) can synchronize and cascade to create a transition to the Ω phase at broader scales, as represented by the "revolt" arrow. Broader scales provide resources during smaller-scale reorganization phase, as suggested by the "remember" arrow.

accumulation of capital over time and an increase in connectivity over space makes the system vulnerable to the destabilizing effect of fast variables that trigger a cascade of creative destruction. This has been described as the “revolt of the slave variable.” Collapse can be initiated by either internal conditions or external events, but typically it is internally induced brittleness (linked to overconnected and accumulated capital) that sets the conditions for collapse, which coincides with a proximal triggering event associated with larger-scale variation (i.e., external events).

Resilience is reestablished by the “remember” process that connects the present to the past (e.g., accumulated seed banks) and the local to the distant (in-dispersal of propagules). It involves processes of regeneration and renewal. In social systems, examples of these connections include drawing upon and utilizing social capital, traditional knowledge, and wisdom. The remember process is also an opportunity for small-scale processes to cause system change during the transition from reorganization to exploitation, that is, from alpha to r . During this reorganization phase, the system is in a state opposite to that of the conservation phase. There is little local regulation and stability, so the system can easily be moved from one state to another. Resources for growth are present, but they are disconnected from the processes that facilitate and control growth. In such a weakly connected state, a small-scale change can nucleate a structure amidst the sea of disorder. This structure can then use the available resources to grow explosively and to establish the exploitative path along which the system develops and then locks into. This transition occurs as small-scale changes sow seeds of order in the larger and slower chaos within which they are embedded. The transient but critically important bottom-up asymmetry provides an opening for evolutionary change. That is, the previous system pattern may reassert itself, or the system may reorganize itself into a novel structure.

In this section, we have reviewed the theoretical and empirical foundations for understanding resilience in complex, adaptive systems. That foundation will be examined in the remaining chapters of this volume. To provide some focus for such evaluations, we have developed a set of propositions. To provide some structure for evaluating the theoretical foundation, we have developed a set of propositions that describe the main claims of these new theories.

Propositions

A theoretical review of the ecological processes organizing large-scale ecosystems leads to a number of propositions. Because these propositions are largely based upon ecological literature, they may be inappropriate in other disciplinary areas.

For this reason, we offer them provisionally, so that their examination and testing focus the following discussion. Our intent is to provide a framework for subsequent chapters to explore, refine, and reject these constructs as they apply to a wide variety of large-scale, ecological systems. In this spirit, we pose the following propositions:

- *The organization of regional resource systems emerges from the interaction of a few variables.* The essential structure and dynamics of complex systems are produced by the interaction of at least three, but no more than six, variables that operate at spatial and temporal scales that differ by approximately an order of magnitude.
- *Complex systems have multiple stable states.* Complex systems can exhibit alternative stable organizations. Transitions between different organizations are due to changes in the interaction of structuring variables. Change often occurs when gradual change in a slow variable alters the interactions among faster variables.
- *Resilience derives from functional reinforcement across scales and functional overlap within scales.* Resilience derives from both a duplication of function across a range of spatial and temporal scales and a diversity of different functions operating within each scale.
- *Vulnerability increases as sources of novelty are eliminated and as functional diversity and cross-scale functional replication are reduced.* Diminished sources of novelty reduce the ability of a system to recover from disturbances. The elimination of structuring species or processes can cause an ecosystem to reorganize. A reduction in functional diversity and duplication of functions reduces the ability of a system to persist.

Evaluation of Propositions in Large-Scale Ecosystems

These propositions are evaluated in the case studies presented in this book. The book itself is divided into three parts: a theoretical introduction, case studies, and synthesis. The theoretical introduction is provided by this chapter and the next, which use a set of mathematical metaphors to describe and deepen our understanding of the concepts of resilience. The second, and largest, part of this volume is a series of case studies that explore the biophysical dimensions of resilience and evaluate the propositions described above. These case studies review resilience in both terrestrial and aquatic systems. The terrestrial systems include boreal forest, tropical rainforest, tropical dry forest, semi-arid savanna, and tropical agroecosystems. Aquatic ecosystems considered include coral reefs, freshwater lakes, wetlands, and inland seas (specifically the Baltic Sea). The book

concludes with a synthesis section, revisiting these propositions in light of the case studies.

Literature Cited

- Allen, C. R., E. Forsy, and C. S. Holling. 1999. Body mass patterns predict invasions and extinctions in transforming landscapes. *Ecosystems* 2:114–121.
- Allen, T. F. H., and T. B. Starr. 1982. *Hierarchy: Perspectives for ecological complexity*. Chicago: University of Chicago Press.
- Arthur, W. B., Y. M. Ermoliev, and Y. M. Kaniovski. 1987. Path-dependent processes and the emergence of macro-structure. *European Journal of Operations Research* 30:294–303.
- Clark, N., and C. Juma. 1987. *Long-run economics: An evolutionary approach to economic growth*. London: Pinter.
- Darwin, C. 1860. *On the origin of species by means of natural selection, or, the preservation of favoured races in the struggle for life*. 5th ed. London: J. Murray.
- David, P. A. 1985. Clio and the economics of QWERTY. *American Economic Review* 75:332–337.
- DeAngelis, D. L. 1980. Energy flow, nutrient cycling and ecosystem resilience. *Ecology* 61:764–771.
- Diener, M., and T. Poston. 1984. On the perfect delay convention or the revolt of the slaved variables. Pp. 249–268 in *Chaos and order in nature*, edited by H. Haken. Berlin: Springer-Verlag.
- Dublin, H. T., A. R. E. Sinclair, and J. McGlade. 1990. Elephants and fire as causes of multiple stable states in the Serengeti-Mara woodlands. *Journal of Animal Ecology* 59:1147–1164.
- Ehrlich, P. R. 1991. Population diversity and the future of ecosystems. *Science* 254:175.
- Elton, C. S. 1958. *The ecology of invasions by animals and plants*. London: Methuen.
- Fiering, M. B. 1982. Alternative indices of resilience. *Water Resources Research* 18:33–39.
- Folke, C., and F. Berkes, eds. 1998. *Linking ecological and social systems*. Cambridge: Cambridge University Press.
- Fragoso, J. M. V. 1997. Tapir-generated seed shadows: Scale-dependent patchiness in the Amazon rain forest. *Journal of Ecology* 85:519–529.
- Gunderson, L. H., C. S. Holling, and S. S. Light. *Barriers and bridges to renewal of ecosystems and institutions*. New York: Columbia University Press.
- Hodgson, G. M. 1993. *Economics and evolution: Bringing life back into economics*. Ann Arbor: University of Michigan Press.
- Holling, C. S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4:1–23.
- . 1991. The role of forest insects in structuring the boreal landscape. Pp. 170–191 in *A systems analysis of the global boreal forest*, edited by H. H. Shugart, R. Leemans, and G. B. Bonan. Cambridge: Cambridge University Press.
- . 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. *Ecological Monographs* 62:447–502.
- . 1996. Engineering resilience versus ecological resilience. Pp. 31–43 in *Engineering within ecological constraints*, edited by P. C. Schulze. Washington, D.C.: National Academy Press.

- Holling, C. S., D. D. Jones, and W. C. Clark. 1977. Ecological policy design: A case study of forest and pest management. In *Proceedings of a conference on pest management*, edited by G. A. Norton and C. S. Holling. Oct. 1976, IIASA CP-77-6, 13-90, Laxenburg, Austria.
- Holling, C. S., G. Peterson, P. Marples, J. Sendzimir, K. Redford, L. Gunderson, and D. Lambert. 1996. Self-organization in ecosystems: Lumpy geometries, periodicities and morphologies. Pp. 346–384 in *Global change in terrestrial ecosystems*, edited by B. H. Walker and W. L. Steffen. Cambridge: Cambridge University Press.
- Jansson, B.-O., and H. Velner. 1995. The Baltic: The sea of surprises. Pp. 292–374 in *Barriers and bridges to renewal of ecosystems and institutions*, edited by L. H. Gunderson, C. S. Holling, and S. S. Light. New York: Columbia University Press.
- Kamien, M. I., and N. L. Schwartz. 1991. *Dynamic optimization: The calculus of variations and optimal control in economics and management*. Amsterdam: North-Holland.
- Lee, K. N. 1993. *Compass and gyroscope*. Washington, D.C.: Island Press.
- Levin, S. 1995. *Biodiversity: Interfacing populations and ecosystems*. Kyoto: Kyoto University Press.
- Light, S. S., L. H. Gunderson, and C. S. Holling. 1995. The Everglades: Evolution of management in a turbulent ecosystem. Pp. 103–168 in *Barriers and bridges to renewal of ecosystems and institutions*, edited by L. H. Gunderson, C. S. Holling, and S. S. Light. New York: Columbia University Press.
- Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: Lessons from history. *Science* 260:17, 36.
- May, R. M. 1973. *Stability and complexity in model ecosystems*. Princeton, N.J.: Princeton University Press.
- McNaughton, S. J., R. W. Ruess, and S. W. Seagle. 1988. Large mammals and process dynamics in African ecosystems. *BioScience* 38:794–800.
- Morris, R. F. 1963. The dynamics of epidemic spruce budworm populations. *Memoirs of the Entomological Society of Canada* 21:332.
- Morton, S. R. 1990. The impact of European settlement on the vertebrate animals of arid Australia: A conceptual model. *Proceedings of the Ecological Society of Australia* 16:201–213.
- Naiman, R. J. 1988. Animal influences on ecosystem dynamics. *Bioscience* 38:750–752.
- O'Neill, R. V., D. L. DeAngelis, J. B. Waide, and T. F. H. Allen. 1986. *A hierarchical concept of ecosystems*. Princeton, N.J.: Princeton University Press.
- Peterson, G. D., C. R. Allen, and C. S. Holling. 1998. Ecological resilience, biodiversity, and scale. *Ecosystems* 1:6–18.
- Pastor, J., and Y. Cohen. 1997. Herbivores, the functional diversity of plant species, and the cycling of nutrients in ecosystems. *Theoretical Population Biology* 51:165–179.
- Pimm, S. L. 1984. The complexity and stability of ecosystems. *Nature* 307:321–326.
- Sinclair, A. R. E., P. D. Olsen, and T. D. Redhead. 1990. Can predators regulate small mammal populations? Evidence from house mouse outbreaks in Australia. *Oikos* 59:382–392.
- Tilman, D. 1996. Biodiversity: Population versus ecosystem stability. *Ecology* 77: 350–363.
- Tilman, D., and J. A. Downing. 1994. Biodiversity and stability in grasslands. *Nature* 367:363–365.
- Varian, H. R. 1992. *Microeconomic analysis*. New York and London: W. W. Norton.
- Volkman, J., and W. E. McConaha. 1993. *Through a glass darkly*. Columbia River