CHAPTER 15

DISCOVERIES FOR SUSTAINABLE FUTURES

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> *I give you fifteen (oops), I mean ten commandments.*
> —Mel Brooks, "History of the World"

In the course of the project that led to this volume, we identified twelve conclusions (Table 15-1) in our search for theories for sustainable futures. Those conclusions are reviewed in this section. That is followed with a final section resolving the paradoxes presented in Chapter 1:

- If collapse and instabilities characterize systems of people and nature, then why are we still here?
- Why have we fallen into a trap where expertise is thought to be the only way to manage uncertainties inherent in these complex systems?

1. Abrupt shifts among a multiplicity of very different stable domains are plausible in regional ecosystems, some economic systems, and some political systems.

After more than twenty-five years of ecological research since these features were described for ecosystems (Lewontin 1969; Holling 1973b), it is now evident that alternate and alternating stable states arise in a wide variety of ecosystems, such as lakes, marine fisheries, benthic systems, wetlands, forests, savannas, and rangelands. The most convincing cases of multiple states are based on the synthesis of several lines of evidence and usually include long-term observations, experimentation, understanding of causation, and comparative studies of many sites. Because of the heavy demands placed on the data, evidence for multiple states will be equivocal in situations where extensive research has not been possible. However, even small probabilities of multiple states (on the order of 10 percent) have powerful

Table 15-1. Summary Findings from the Assessment of Resilience in Ecosystems, Economies, and Institutions

Summary Statement	Conclusion
Multistable states are common in many systems.	1. Abrupt shifts among a multiplicity of very different stable domains are plausible in regional ecosystems, some economic systems, and some political systems.
The adaptive cycle is the fundamental unit of dynamic change.	2. An adaptive cycle that aggregates resources and periodically restructures to create opportunities for innovation is a fundamental unit for understanding complex systems from cells to ecosystems to societies to cultures.
Not all adaptive cycles are the same, and some are maladaptive.	3. Variants to the adaptive cycle are present in different systems. These include physical systems with no internal storage, ecosystems strongly influenced by external pulses, and human systems with foresight and adaptive methods to stabilize variability. Some are maladaptive and trigger poverty and rigidity traps.
Sustainability requires both change and persistence.	4. Sustainability is maintained by relationships among a nested set of adaptive cycles arranged as a dynamic hierarchy in space and time—the panarchy.
Self-organization provides the arena for change.	5. Self-organization of ecological systems establishes the arena for evolutionary change; self-organization of human institutional patterns establishes the arena for future sustainable opportunity.
Three types of learning can be identified.	6. Panarchies identify three types of change—incremental, lurching, and transforming—each of which can generate a correspondingly different kind of learning.
The world is lumpy.	7. Attributes of biological and human entities form clumped patterns that reflect panarchical organization, create diversity, and contribute to resilience and sustainability.
Functional diversity builds resilience.	8. Functional groups across size classes of organisms maintain ecosystem resilience.
Tractability comes from a "Rule of Hand."	9. Being as simple as possible, but no simpler than necessary leads to the "Rule of Hand." Understanding a panarchy and its adaptive cycle requires a model of a least 3–5 key interacting components, 3 qualitatively different speeds, and nonlinear causation. Vulnerability and resilience of the system change with the slow variables. Spatial contagion and biotic legacies generate self-organized patterns over scales in space and time.
Systems of humans and nature can behave differently than their parts.	10. Linked ecological, economic, and social systems exhibit emergent behavior. The behavior is a result of strong connectivity between the human and ecological components and the presence of nonlinearity and complexity, as suggested in the "Rule of Hand."
Management must cope with surprise and unpredictability.	11. Managing complex systems requires confronting multiple uncertainties. These can arise from technical consideration, such as model structure or analytic framework. The examples suggest that as much complexity exists in the social dimensions as in the ecological ones, and that managers must juggle shifting objectives.
Adaptive management outperforms other management approaches.	12. Slow variables, multistable behaviors, and stochasticity cause active adaptive management to outperform optimization approaches that seek stable targets.

leverage in decision analyses where the costs of sliding into an undesirable state are severe.

Alternative stable domains in ecological systems become evident when shifts occur in the control of key ecosystem processes and structure. These controls can be switched by a variety of human activities. One such switch is associated with a decrease in disturbance variability, such as the change in timing and magnitude of forest pest outbreaks following attempts to control insect populations (Clark et al. 1979; Ludwig et al. 1978). In other cases, it is acceleration of the rates of change of "slow" variables that results in a loss of resilience or shrinkage of a stability domain. The increased rates of nutrient addition to many freshwater lakes and wetlands, for example, have resulted in abrupt flips in the composition and structure of organisms (Carpenter 2000; Scheffer 1998; Chapters 7 and 8). In other ecosystems, it is the change in abundance of key structuring organisms that results in the shift in stability domains. Examples of these include overfishing that leads to changes in trophic structure in coral reefs (McClanahan et al. 1996; Done 1992) or freshwater lakes (Carpenter and Kitchell 1993; Scheffer 1998). Another example is the loss of drought-tolerant species in semiarid rangelands (Walker 1988; Chapter 11), which leads to conversion from grasslands to shrublands. In all of these cases, economic and social systems must manage and adapt to these abrupt shifts in ecological state.

Some economic and social systems also exhibit multiple states. Convergence clubs in economic growth theory are an example (Barro 1997). Multiple states arise in pluralist politics when different units of government, scaled in proportion to the problems they are purported to solve, lead to different outcomes and different organizational frameworks (Chapter 6).

2. An adaptive cycle that aggregates resources and periodically restructures to create opportunities for innovation is a fundamental unit for understanding complex systems from cells to ecosystems to societies to cultures.

Three properties seem to shape the response of the ecosystems, agencies and people in the case examples of regional development and ecosystem management. These properties include the accumulation of potential, the degree of connectedness of elements, and the resilience of the system (Chapter 2). The interaction among these properties creates the four phases of the adaptive cycle (r, K, Ω, and α, Figures 2-1 and 2-2).

One property is the potential acquired from the accretion or accumulation of resources, inventions, and mutations—biological, ecological, social, or economic. In ecosystems, potential can be measured, in part, by production of biomass or nutrients accumulated as a consequence of ecosystem successional dynamics (Carpenter, Ludwig, and Brock 1999; Chapter 7). Social or cultural potential can be represented by the character of human relationships—friendships, mutual respect, and trust among people and between people and institutions of governance (Chapters 5 and 13). In the economy, potential can be represented by the economic capital provided by usable knowledge and skills that are available and accessible (Chapter 10).

The second property is connectedness. It represents the strength of internal connections that mediate and regulate the influences between inside processes and the outside world—essentially, the degree of control that a system can exert over exogenous variability. An organism, ecosystem, organization, or economic sector with high connectedness is little influenced by external variability; its operation and fate are determined by internal regulatory processes that mediate or control variability. It could be measured near equilibrium stability—of speed of return after a small disturbance, for example. Or, less technically, it could be measured by the intensity of control by direct human activity (Carpenter, Brock, and Hansen 1999).

The third property is resilience, or its opposite, vulnerability. We use resilience in its ecosystem sense (Holling 1973b, 1996) to represent the capacity of a system to experience disturbance and still maintain its ongoing functions and controls. A measure of resilience is the magnitude of disturbance that can be experienced without the system flipping into another state or stability domain (Chapters 7 and 11).

These three properties shape a dynamic of change. An example of a linked ecosystem/economic model where output is expressed by changes in all three properties is shown in Chapter 7, Figure 7-7, and in Chapter 9. Potential sets limits to what is possible. Connectedness determines the degree to which a system can control its own destiny. Resilience determines how vulnerable it is to external disturbance that can exceed or break that control.

This was the foundation for the description of an adaptive cycle (Holling 1986, 1992; Figures 2-1, 2-2), where periods of slow accumulation of resource or of environmental or social potential are interrupted by sudden and rapid reorganization of that potential. It is at that moment that experiment and novelty can appear. The consequences can be simply a repetition of the previous cycle, or they can be the initiation of a novel new pattern of accumulation, or they can be the precipitation of a collapse into a degraded state.

The adaptive cycle in its most general form is a metaphor that has some relevance to a number of systems (Table 15-2). But it should not be read as a rigid, predetermined path and trajectory, for ecosystems at least, let alone economies and organizations. What are suggested are waxing and waning tendencies, with various degrees of predictability at different stages. All actors and species can be present throughout—pioneers, consolidators, mavericks, revolutionaries, and leaders. Their role and significance change as their actions create the cycle. The four phases of the cycle can overlap, but the most distinct separation is between K and Ω. That is the shift that occurs as a stability region collapses, or as a disturbance moves variables into another stability domain. But even the most predictable sequence, from r to K, can be diverted by extreme or episodic events.

The phases of the cycle are also useful to understanding the practice of resource management. Local and traditional systems have developed a rich variety of practices (in many cultures and geographic areas) that interpret and respond to feedback from these complex ecosystems. They include practices that mimic disturbance at lower scales of the panarchy and that nurture sources of renewal. Instead of removing or eliminating disturbance altogether, local and traditional adaptations seem to accept perturbations as an intrinsic part of ecosystem dynamics and focus instead on "putting the brakes

Table 15-2. Some Examples of the Four Phases of the Adaptive Cycle (see Figures 2-1 and 2-2)

System Type	**Phase of Adaptive Cycle**				**Reference**
	r	K	Ω	α	
Ecosystems	exploitation	conservation	release	reorganization	Holling 1986; Chapter 2
Economies	market, entrepreneur	monopoly, hierarchy	creative destruction	invention	Schumpeter 1950
Organizations	adhocracies	bureaucracy routinization	catalysts, heretics	visionary	Westley 1995; Chapter 13
Institutions	markets	hierarchies	sects	isolates	Thompson 1983; Chapters 6 and 9
Individuals	sensation	thinking	intuition	feeling	Jung, as in Mann et al. 1976

on release" by managing the magnitude and frequency of release. These practices are in contrast to bureaucratic, western systems, where the focus is on eliminating disturbance through stabilization of key variables. This inevitably leads to management crises. Navigation through these crises by western approaches is problematic, messy, and contingent (Chapters 6, 11, 12, and 13). This theme is developed later.

3. **Variants to the adaptive cycle are present in different systems. These include physical systems with no internal storage, ecosystems strongly influenced by external pulses, and human systems with foresight and adaptive methods to stabilize variability. Some are maladaptive and trigger poverty and rigidity traps.**

In the course of using the adaptive cycle as an organizing metaphor for understanding system dynamics, researchers found the behavior of a number of systems to represent variants from the general pattern (Chapter 2). The exceptions are related to differences in the ability of a system to create novelty and to deal internally with external variation. These exceptions fall into at least four categories: (a) physical systems with no ability to create novelty, (b) living systems with evolved components that adapt passively to variation, (c) living systems with evolved components that manage variation actively over some ranges of scale, and (d) human systems with foresight and intentionality that both control variability and create novelty. These four are expanded on below:

a. Physical systems lack chance inventions and mutations and therefore limit their potential for evolutionary change. In these systems there is little or no accumulation of novel potential (e.g., mutation, inventions, or exotics) that can subsequently act to transform the system response. Examples include tectonic plate dynamics and Bak's (1996) sandpile experiments. Each system exhibits periods of instability and reorganization, but novelty and mutation are not created and rearranged to the same degree as in living systems.

b. Living systems can have different strategies for dealing with variability, depending on whether their environment is controllable or predictable. If it is neither, the strategy is to live passively with variability by individuals evolving extensive adaptations to variability. Such ecosystems have an adaptive cycle largely restricted to the r and alpha phases. Pelagic, open water communities and eroded semiarid savannas exposed to rare and unpredictable episodes of rain are examples.

c. Living systems that can control variability, over some scales, show the full cycle of the four phases, of growth, rigidity, collapse, and reorganization. Examples are productive temperate ecosystems and large bureaucratic organizations.

d. Human systems with foresight and intentionality can uniquely manage variability creatively, in order to minimize or prevent instabilities and retain flexibility. Forward expectation markets that deal with resource scarcity are one such example. Another example includes large organizations that attempt to maintain creativity by converting organization-wide boom-and-bust cycles to smaller, internal learning cycles. In such human systems we might identify ways to anticipate and manipulate variability creatively, and escape the apparent inevitability of the adaptive cycle and its prediction of rigidity leading to crisis.

4. Sustainability is maintained by relationships among a nested set of adaptive cycles arranged as a dynamic hierarchy in space and time—the panarchy.

The panarchy is a nested set of interacting adaptive cycles arranged in a hierarchy across scales in space and time. It represents the dynamic interplay between the processes and structures that sustain relationships on the one hand, and those that accumulate potential on the other. The concept is sufficiently new that precise insights and prescriptions are just beginning to be made. Many of the alternative stable states mentioned above are situations in which panarchies are transformed, either because productive novelty cascades up the levels or because destructive catastrophes cascade down.

The adaptive cycle is the engine that periodically generates the variability and novelty on which experimentation and change depend. As a consequence of the adaptive cycle and its periodic but transient phases of creative destruction (Ω phase) and renewal (α phase), each level of a system's structure and processes can be reorganized. This reshuffling allows the possibility of new system configurations and opportunities from the incorporation of exotic and entirely novel entrants that accumulated in earlier phases.

For organisms, those novel entrants are mutated genes, or for some bacteria, exotic genes transferred occasionally between species. For ecosystems, the novel entrants are exotic species, or species "in the wings" waiting for more appropriate conditions. For economic systems, those novel entrants are inventions, creative ideas and people that emerge in the earlier phase of growth where they were constrained from further development of their potential. The adaptive cycle explicitly introduces a slow period of growth in which mutations, invasions, and inventions can accumulate, followed by a brief period of rearrangements. It is a periodic process that can occur within each hierarchical level, in a way that partially isolates the resulting experiments, reducing the risk to the integrity of the whole structure.

Novelty can be generated, tested, and selected in the constituent adaptive cycles of the panarchy and can then spread to other levels. Many times, the source of novelty lies not so much in de novo entities like inventions, mutations, and exotics but in novel, unpredictable combinations of those with existing components that can suddenly establish new domains of influence, opening an entirely new set of adaptive pathways. Examples include the sixty-year wave of technological innovation initiated in the nineteenth century and the Internet in the later part of the twentieth century. These were triggered not simply by single new inventions (e.g., the steam engine or the personal computer), but by the context of a whole economy and society that had accumulated a set of rigidities and novelties that precipitated, synergized, and directed a transformation (Schumpeter 1950; Fischer 1996).

Levi-Strauss (1962) coined the word *bricolage* for this process of recombining existing elements and new mutations and inventions to form something novel that solves a newly emerged problem or creates new opportunity. The adaptive cycle accumulates those elements as potential and then, for transient moments, rearranges them for subsequent testing in changing circumstances. Those of consequence can nucleate new opportunity and accumulate further potential. If that accumulated potential exceeds a threshold, it can cascade upward in the panarchy and create new panarchical levels.

Such transformations are qualitatively different from the incremental changes that occur during the growth phase of the adaptive cycle. They are also qualitatively different from the potentially more extreme changes and frozen accidents that can occur during the more revolutionary shift in the adaptive cycle from creative destruction (Ω) to renewal (α). They cascade and transform the whole hierarchy and its constituent adaptive cycles. They are panarchical transformations. Such transformations and the panarchies that create them provide a robust theoretical foundation for sustainability.

The organization and functions we now see embracing biological, ecological, and human systems are therefore these that contain a nested set of the four-phase adaptive cycles, arranged in a dynamic hierarchy, in which opportunities for periodic reshuffling within levels create novel adaptive opening and the simple interactions across levels conserves the ability to test, propagate or smother those opportunities (Chapter 3). What distinguishes the biological, ecological, and human systems from one another is the way inventions are accumulated and transferred over time—through genes, self-organized patterns, or communication.

Panarchies succinctly summarize the property that we define as sustainability. The fast, small levels invent, experiment, and test; the slower, larger levels stabilize and conserve accumulated memory of past successful, surviving experiments. The whole panarchy is both creative and conserving. The interactions between cycles in a panarchy combine change with continuity (Chapter 3, Figure 3-5). That clarifies the meaning of sustainable development. Sustainability is the capacity to create, test, and maintain adaptive capability. Development is the process of creating, testing, and maintaining opportunity. The phrase that combines the two, *sustainable development*, rather than being an oxymoron, represents a logical partnership.

5. Self-organization of ecological systems establishes the arena for evolutionary change; self-organization of human institutional patterns establishes the arena for future systainable opportunity.

The Ecological Theater and the Evolutionary Play, the evocative title of a book of essays by G. E. Hutchinson (1965), captures the notions that ecological context influences the course of natural selection and that the results can further reinforce the ecological context. Selective pressures come also from aspects of the physical-chemical environment, such as geomorphology, hydrology, biogeochemistry, and climate. Evolution, in turn, shapes ecosystems because ecological systems are self-organized from evolved components, as Levin (1999) describes in *Fragile Dominion*. Those self-organized components include some suites of organisms that create patterns and are reinforced by those patterns (Holling 1992). Others act as "ecological engineers," altering the physical structure and especially the biogeochemistry of ecosystems (Jones and Lawton 1995). Thus the interplay of evolution, ecology, and the physical-chemical environment is an intricate dance, in which configuration and control change eternally. Humans develop self-organized patterns more intensively and over much larger ranges of scale than other organisms do. We conjecture that those self-organized patterns are as important for evolution as Darwinian natural selection, and as important for sustainable development as the market.

The panarchy is created by these self-organizing processes within the constraints set by physical laws. The phases within the constituent adaptive cycles are highly dynamic and variable, the adaptive cycle itself is less so, and the full panarchy is highly conservative. The resulting ecological panarchy is a template sustained by living processes and reinforcing those same processes. Different sets of those processes function at different scales of ranges, producing a sustained, conservative pattern of eddies of productivity and opportunity across scales.

6. Panarchies identify three types of change—incremental, lurching, and transformational—each of which can generate a correspondingly different kind of learning.

Incremental change and learning. This type of change occurs in the predictable development phase or from the r to K phases of the adaptive cycle (Figure 2-1). During these phases, models or schemas are assumed to be correct, and learning is characterized by collecting data or information to update these models. This type of learning is similar to the single-loop learning of Argyris and Schon (1978). In bureaucratically dominated resource systems, the activity of learning is carried out largely by self-referential professionals or technocrats who primarily view dealing with this type of change and learning as problem solving (Chapter 13).

Abrupt change and spasmodic learning. This type of change is episodic, discontinuous, and surprising. It is created by slow-fast dynamics that reveal the inadequacies of the underlying model or schema structure. It is the change described by transitions from the conservation phase (K) through the creative destruction (Ω) and renewal (α) phases of the adaptive cycle. This can be manifested as an environmental crisis, where policy failure is undeniable (Gunderson et al. 1995a) and results from an environmental cognitive dissonance. In this case, the learning is described as double loop, in which the underlying model or schema is questioned and rejected (Argyris and Schon 1978). This is also characterized as problem reformation. In bureaucratic resource systems, this type of learning is facilitated by outside groups or charismatic integrators.

Transformational learning. This is the most dramatic type of change and requires the deepest type of learning. Cross-scale or novelty surprises characterize this type of change and are related to interaction between different sets of labile variables. In these cases, learning involves solving problems of identifying problem domains among sets of wicked and complex variables (Chapter 13). Transformational learning involves several levels in a panarchy, not simply one level. This is also described as evolutionary learning (Parson and Clark 1995), in which not just new models or schema are developed, but also new paradigmatic structures (*sensu* Kuhn 1962).

7. Attributes of biological and human entities form clumped patterns that reflect panarchical organization, create diversity, and contribute to resilience and sustainability.

Ecological, economic, and human systems can exhibit scale invariant properties that can be fit to continuous functions. The current emphasis on power laws in complex systems research provides examples. But, in addition, in ecosystems, the pattern of morphological and geometric attributes of entities along those continua exhibit clumped structures (Holling 1992; Chapter 3). Moreover we show that such clumped structures of attributes are associated with a range of impacts of considerable ecological and evolutionary consequences. Among plants, these include species performing critical ecosystem functions (Walker et al. 1999). Among animals, these include species that are the indicators and creators of change: those that are endangered, invasive, nomadic, and migratory (Allen et al. 1999). This structure and its associated species diversity determine resilience.

Panarchies of living systems, social as well as ecological, provide a discontinuous template in space and time that entrains attributes of variables into a number of distinct lumps. By lumps we not only mean the discrete aggregates that Krugman (1996) describes for human settlements. There are such discrete aggregates in ecosystems—some very obvious, like individual organisms; some more amorphous, like plant associations and ecosystems themselves. But in addition, we mean that attributes of size, speed, and function of those discrete aggregates should be distributed in a lumpy manner.

Those attributes could be periodicity of fluctuations, size of objects at different scales on a landscape, scales of decision processes of animals and humans, or morphological and functional attributes of animals and plants.

Evidence of these lumpy patterns has been found in the morphology of organisms for a number of taxa (mammals, birds, insects, herpetofauna, and plants) in a number of different ecosystems in dry and wet regions, cold and hot ones, in lakes, on land, and in the benthos. The patterns are very conservative and persistent, changing only under extreme disturbances. We propose that they reflect the conservative, sustaining nature of ecological panarchies.

There are two reasons an ecosystem or landscape would create a lumpy template. One is the discontinuous nature of the processes that form different levels of the panarchy. Those are the processes that create a disjunct separation of scales among key structuring variables. The other is the nature of the adaptive cycle itself at each level of the panarchy. The phases of the cycle are distinct, and the shift in controls from one to another is abrupt, because the processes controlling the shifts are nonlinear and the behavior multistable. Each phase creates its own distinct conditions, which in turn define distinct attributes of size and speed of aggregates that control the phase or are adapted to its conditions. K-species and firms tend to be big and slow; r-species and firms tend to be small and fast. We are not saying that the four phases of a cycle entrain four lumps, though it would be fun to develop a test of that hypothesis. We are saying that the combination of panarchy-level discontinuities and adaptive cycle discontinuities will generate a number of lumps, the number defined by the resolution of the observations and the range of scales tested. Panarchies form a lumpy template that entrains the same lumpy attributes in organisms that create or are part of them.

We conjecture that some social and economic systems will exhibit the same structures. Barro (1997), for example, groups countries into economic lumps called convergence clubs. Countries within a given club have economic growth performances that tend to converge. These patterns of growth performance across countries appear to be structured by movement toward a long-term "target" rate of growth for each country, where the long-term target is determined by slow and medium time scale variables. Slow processes of governance establish the degree of flexibility, trust, and freedom of institutional and political structures. Medium-speed processes set the general level of public physical infrastructure and education.

We hypothesize that these clumped structures can concentrate opportunity and potential and maintain resilience and adaptive capability across scales.

8. Functional groups across size classes of organisms maintain ecosystem resilience.

Biodiversity contributes resilience to the functioning of an ecosystem. Its functions arise from the interaction of a diverse set of biotic and physical processes that control net carbon assimilation and transpiration, water extraction from various soil layers, nutrient cycling and retention, herbivory, and predation. Chemical and physical processes interact with processes mediated by critical species in the biota.

These species can be divided into functional groups based on differences in their ecological functions. The different functions of plants are represented by attributes such as nitrogen-fixing capacity, rooting depth, water-use efficiency, and litter decomposition rate. For animals they are represented by trophic status, body mass, and foraging class.

Adequate performance of ecosystem function depends on having all the necessary functional groups (the full array, or diversity, of functional groups) present. The persistence of ecosystem function over time (i.e., the resilience of ecosystem function) depends on the diversity of species within functional groups. There are two important forms of diversity within functional groups: one providing functional compensation within a narrow range of scales and one providing functional reinforcement across a wide range of scales (Chapter 3).

Functional compensation within a narrow range of scales occurs when species perform a similar function but have different environmental sensitivities. For example, if one species of nitrogen fixer is greatly reduced in abundance, or eliminated by a disease or an extreme temperature, other nitrogen-fixing species that are resistant to the disease or have different temperature responses are able to substitute for it. A study of functional attribute diversity of an Australian rangeland (Walker et al. 1999) revealed that the most abundant plant species were far apart from each other in plant-attribute space (i.e., they perform different functions). However, among the less abundant species, at least one species was functionally very similar to each abundant species. Furthermore, on a site that had been heavily grazed, dominant species that had been eliminated were replaced by a functionally similar species that was less abundant on a lightly grazed site. It is an example of resilience achieved from functional compensation within a scale range.

Important generalizations concerning the role of biodiversity have recently been developed using ecological experiments in laboratory and field settings (Naeem et al. 1994; Tilman 1996; Tilman et al. 1996; Kassen et al. 2000). However, the size of enclosures and quadrats in these experiments was, for practical necessity, small relative to the full range of processes represented by ecological panarchies, i.e., centimeters to a few meters and days to a few years, rather than meters to hundreds of kilometers and months to centuries (Figures 3-2 and 3-3). The conclusions of these experiments therefore exclusively concern functional compensation within a (small) scale range. In contrast, conclusions concerning the role of biodiversity across scales comes from regional scale studies of ecosystems, where modeling, process understanding, and management interventions combine to allow analysis of larger parts of the panarchy and the multiple scales they represent. Those studies reveal an additional and different role for biodiversity in providing cross-scale reinforcement.

Cross-scale functional reinforcement occurs when species perform similar ecological functions but at very different scales. It allows function to persist despite environmental variation and endogenous cycles, because of overlapping reinforcement of their effects. For example, small birds that glean individual larvae from conifer needles usually maintain regulation of forest insect pest populations (like those of the spruce budworm) over long periods at low levels in young forests. However, if budworm populations increase, birds of progressively larger body sizes begin to prey on them (Holling 1988; Peterson et al. 1998). This cross-scale functional reinforcement is able to maintain effective predation on budworm population over a much larger range of budworm population densities than would a set of foragers that operate at only the same scales.

In addition, the cross-scale functional reinforcement of ecological function enhances the ability of an ecosystem to reestablish itself following disturbance. Species that operate at a small scale may survive a larger disturbance by continuing to persist in the interstices of a disturbed area. Large animals are able to avoid a smaller-scale disturbance. For example, dispersal of palm seeds can occur in a deforested patch of forest, in the absence of dispersers within a patch, if large animals pass through the patch, bringing seeds from the surrounding forest (Peterson et al. 1998). Decreases in cross-scale functional reinforcement, therefore, will likely reduce the ability of ecosystems to recover from disturbance.

These two effects of diversity do not represent the effects of redundancy in the replicated sense that an engineer might apply it to achieve engineering reliability. Rather, for functional compensation, each species in the same scale range has a similar function but different responses to unanticipated environmental change. If the ecosystem were a theater, the species within such a narrow scale range would be like multiple stand-in actors prepared to replace each other in the event of unexpected external surprises and crises. For cross-scale functional reinforcement, species in different scale ranges can also engage in similar or related ecosystem functions, but, because of their different sizes, they differ in the scale and degree of their influence. In our ecosystem theater, species in different scale ranges are like actors waiting in the wings to facilitate a change in pace or plot when needed. The within-scale and between-scale diversity produces an overlapping reinforcement of function that is remarkably robust. We call it imbricated redundancy.

Such imbricated redundancy of species in ecosystems is a critically important mechanism for ensuring resilience of ecosystem function. It is a serious error to assume that minor species are indeed "passenger" species that can afford to be lost. It may be difficult to detect the importance of species if they are providing compensation or performing a function over broad spatial or time scales. The importance of such species may be detected only when they are needed, following a disruption. In addition, the ability of ecosystems to recover from disturbance may be decreased by the loss of species, especially those that operate over large scales. In the absence of those species, ecosystems may reorganize in response to formerly tolerable disturbances

9. Being as simple as possible but no simpler than necessary leads to the "rule of hand."

The minimal complexity needed to understand a panarchy and its adaptive cycles (Chapter 2) requires:

- three to five key interacting components
- three qualitatively different speeds of variables
- nonlinear causation and multistable behavior
- vulnerability and resilience that change with slow variables
- creation of structures by biota and reinforcements of biota from structure
- spatially contagious processes to generate self-organized patterns

Anyone contemplating a theory of sustainability confronts a vast diversity of entities, variables, and processes that could be included in models. The art of modeling is to suppress detail; focus attention on broad, crosscutting phenomena; and develop powerful, general, and testable ideas. It does not matter that the model will ultimately prove to be inadequate, or at best reliable within only a limited domain. Rather, we derive insight and ideas from the learning process associated with building, evaluating, discarding, and revising models. As noted by George Box (1976), "All models are wrong, but some are useful."

We chose to begin with models that were simple, but not too simple. We added detail only grudgingly, as the dissonance between models and the systems we sought to understand became unacceptably large. As examples of models that are too simple, consider the models of the disciplines we sought to integrate. Ecological models do not generally include the forward-looking behaviors of large numbers of interacting agents, which are central to economic and social models. Socioeconomic models do not generally address the multiscale hierarchies of ecological systems and are just beginning to consider the difficulties posed by slow social and ecological variables. By definition, the individual disciplinary models are too limited, although they offer useful component models and mathematics for building the more integrated models that we seek.

As one foundation for appropriately simple models, we have the ecologists' rule of hand. It is not a mathematical theorem; rather, it is a loose guideline for developing ecological and linked ecological and economic models that are complex enough to generate revealing and testable predictions, but simple enough to understand. Such models have at least three, and perhaps as many as five, interacting components (hence "rule of hand"; a rule of thumb would have only one component). The components of the model exhibit at least three quite different (by around tenfold) turnover times. Some of the linkages among components are nonlinear in the state variables (not necessarily in the parameters). The slow variables create a stability landscape with multiple attractors. Because the slow variables are dynamic and have feedbacks with the fast variables, the stability landscape is itself dynamic, so transitions among attractors are possible.

How do we decide that a model is overly simple and that additional detail is needed? We ask whether the model can address the phenomena we seek to understand and explain the facts known to us. If not, the model must be discarded or revised. Early in the project we discovered that the rule of hand was necessary for ecosystem models but too simple for linked ecosystem, economic, and decision models (see Chapters 3 and 7). In those situations it was necessary to both include three speeds of key variables and consider the emergence of economic patterns from individual actions of many forward-looking agents. These agents must cope with difficulties of learning about the slowly changing variables in ecological systems. And these agents act within dynamical structures of social legitimation, domination, and signification, themselves functioning at three speeds (Chapter 13).

The pathway to our next generation of models involved several experiments (Carpenter, Brock, and Hanson 1999). In each, we combined a simplified, three-speed ecological model with a model of forward-looking, boundedly rational agents engaged in economic and political activity. This sequence of experiments led to the models represented in this book (Chapters 7, 8, and 9). These models include an ecological system consistent with the rule of hand. In addition, we model a technologically based management agency based on examples known from many democracies. The agency gathers data about the ecosystem and economic system. The information is used in a decision-making process that promulgates regulations and incentives designed to guide the actions of many individual agents. Each of the agents has some effect on the ecosystem, which the agents share. Although the agents are individualistic, they are cocreating a common environment. Their actions are guided by learning about this environment and the behavior of the agency and external markets. An individual's actions are based on his or her forecasts of how various choices will affect his or her well-being.

While this family of models has proven to be a rich source of insight and ideas (Chapters 7, 8, 9, and 10), we have a growing list of interesting problems that they cannot address. As we grow dissatisfied with the limited domain of the existing models, we will enter a new adaptive cycle of our own research, creating the next generation of models. Some challenges for the future are as follows: (1) How is the self-organization of ecological systems, and the adaptive landscape for evolution, affected by social activity? (2) How do different social systems affect the potential for evolutionary change and the origins of biotic novelty? (3) How does the interaction of ecological learning with social dynamics affect resilience? Some approaches to forecasting encourage cautious experiments that lead to adaptive change and sustained or growing resilience. Others lead to risky behavior or social rigidification, which may shrink resilience or cause collapse. These raise fundamental questions about the interactions of science and society related to foresight and sustainability.

10. Linked ecological, economic, and social systems exhibit emergent behavior.

Integrated systems exhibit emergent behavior if they have strong connectivity between the human and ecological components, and if they have key characteristics of nonlinearity and complexity. Those key characteristics of the socioeconomic system include many individual, boundedly rational agents or institutions making decisions (using formal or informal rules) and learning about a world they cocreate (Carpenter, Ludwig, and Brock 1999; Janssen and Carpenter 1999). Those key characteristics for ecosystems are described in the rule of hand above.

A common pattern in the dynamics of these linked systems is that stabilization of one or more of the subsystems inevitably leads to instabilities or collapse of the whole. This is manifest as a loss of resilience in the ecological components or loss of adaptive capacity in the human components. Perhaps ecological collapses, and the subsequent need to innovate, create, reorganize, and rebuild, are a likely, maybe even inevitable, consequence of human interactions with nature.

Ultimately, the risk of collapse under apparently optimal management traces to slow variables that are mistakenly assumed to be static, a broad probability distribution of uncertainties, shortsightedness due to discounting of the future, and losses of social flexibility and ecological resilience. Therefore, institutions that counter these trends may help ameliorate the risk or severity of collapse. Such forward-looking policies can be introduced during the backloop (Ω to α to r phases) of the adaptive cycle. In these phases, relatively simple models can serve as the focus for activities designed to evoke insight, creative debate, and cooperative learning. The models are heuristic devices that simulate reality, give insight into possible human choice mechanisms and their interactions with ecosystems, and for the practitioner provide a chance to explore implications of possible interventions.

Carpenter, Brock, and Ludwig (1999) indicate situations where even if the ecological components of the system are known perfectly, environmental stochasticity and changing human dynamics contribute to destabilization, collapse, and renewal. This suggests that what is needed is not just research on the disciplinary components of these systems, but rather a broader, integrative view that helps develop understanding as much as analysis. Other contributors to this volume begin to suggest how people deal with such fundamental uncertainties.

11. Managing complex systems requires confronting multiple uncertainties.

We began this volume with a series of paradoxes or contrasts that arose from mostly western, bureaucratic approaches to resource management. In the process of resolving those paradoxes (which is done in more detail below), we looked to a variety of alternative viewpoints to see how people manage to manage these complicated systems. Those perspectives were from analysts of traditional approaches to management (Chapter 5), political systems (Chapter 6), social systems (Chapter 8), and economics (Chapter 10) and from experiences of practitioners (Chapters 11, 12, and 13). A common thread that wove through these chapters surmised that these systems are so difficult to manage because of the multiple sources of uncertainty that confront any practitioner. These range from concepts of how people begin to understand and monitor the ecosystem, to the myriad of ways people confront, test, and resolve those uncertainties from myths to institutions, and the complexities of action in the linked system.

Local and traditional practices confront uncertainties of resource dynamics through a number of mechanisms. Berkes and Folke (Chapter 5) argue that traditional approaches are based on a dynamic concept of nature that manages *with* environmental variation rather than against it. Traditional approaches use long time series of local observation and institutional memory to deal with infrequent (at least on a human time scale) and little experienced environmental fluctuations. This experience accrues in "traditional knowledge" that is culturally transmitted and evolves through adaptive processes. Knowledge carriers, such as elders, play a crucial role in this institutional memory of ecosystem change. So do myths and rituals, by helping people remember the rules and interpret environmental signals. Qualitative monitoring is key to testing this traditional knowledge base.

The development of an array of political institutions and settings appears key to managing certain types of uncertainties, yet the contributors paint a messy, mixed picture of success. As stressed by Pritchard and Sanderson (Chapter 6), there is no magic or singular fix to the design of institutions and implementation of policies to cope with the types of ecologic dynamics mentioned earlier. Indeed, the authors point out the weakness of approaches that are based on administrative rationality, market rationality, pluralist politics or communitarianism in dealing with these "wicked problems." Notwithstanding the optimism of economics to optimize and prescribe policies under a small set of preconditions (Chapter 10), these authors emphasize the dynamic or fluid nature of policies and institutions, as captured by their metaphor of politics as a "floating crap game." These authors discuss the failure, invention, creation, or reinvention of institutions as a common pattern and suggest participatory pluralist approaches to help bridge differences between local knowledge and broader-scale issues and perspectives. They caution about the difficulties of implementation in a context of there being no best approach, a theme reinforced by other contributors.

In the one example from the front line, a scientifically based western resource manager, complications at a micro level only compound these complexities (Chapter 13). Uncertainties arise from the dynamics of multiple social groups within which the manager must operate. The political arena, the organizational objectives, and the stakeholder (or interorganizational) preferences all must be juggled with the implementation of a science-based approach. None of these subsystems can be considered alone to help understand the interactive dynamics of social system and ecosystem that confront the adaptive manager. Rather, the entire network of interacting individuals and organizations at all three levels represents the social system. It is clear, therefore, that to manage adaptively is a question of creating the right links, at the right time, around the right issues to create a responsive system. As noted above, it is not a question of identifying best practices or institutional arrangements.

All of the contributors who reported on the successes and limitations from a practitioner's perspective discuss an approach that was deliberately developed to confront and resolve the uncertainties of resource issues through a process called adaptive management (Holling 1978; Walters 1986; Lee 1993; Gunderson et al. 1995a). Some conclusions about the efficacy of this approach are described in the final section.

12. Slow variables, multistable behaviors, and stochasticity cause active adaptive management to outperform optimization approaches that seek stable targets.

Walters (1997), Johnson et al. (1999), Gunderson (1999a), and the cases in this volume have stressed the practical difficulties that humans face in attempting to manage ecosystems. The multiple scales of variables, cross-scale, and nonlinear interactions generate the multistable behaviors in ecosystem dynamics. The surprises generated by this multistable behavior create a range of problems for management. Some of the difficulties are caused by lack of knowledge of the dynamical system (which may possess a very large state space and be nonstationary, as well as not being known). Other difficulties are caused by measurement error in state variables even if they can be properly identified. For example, Carpenter assessed the key sets of variables in one of the most studied and measured ecosystems in the world (Lake Mendota) and concluded that it is impossible to determine a priori when a change of state will occur. This is due to the interaction between slowly changing variables that influence the vulnerability of the system, and the faster, stochastic variables, as described in Chapters 2, 3, and 7. All of these compound the difficulties of managing, much less managing adaptively.

Adaptive management in its early form focused on confronting the uncertainty of resource dynamics through actions designed for learning (Holling 1978; Walters 1986). This has evolved from a problem of testing a single hypothesis about the system to sorting among multiple hypotheses, each of which may have different social and management implications (Gunderson 1999a). Other layers of complexity arise from having inadequate monitoring or data to put these hypotheses at risk (Walters 1997). Ludwig (1995) considers harvesting strategies under increasing layers of uncertainty and shows that increasing uncertainty generally leads to increasing caution in harvesting and a strengthened precautionary principle. The challenges posed have a technical dimension and a social dimension. First the technical one.

The technical challenge has two parts as well: the first is to develop a framework that will allow for a process of formulating testable hypotheses; and the second is to choose among multiple hypotheses. The types of models of complex adaptive systems presented in Chapters 7, 8, 9, and 11 appear to be a useful framework for the problem of formulating hypotheses. These have a long history of use in the process of adaptive assessment (Walters 1997). The process of making the model is much more important than the model itself (Walters 1986). The technical challenges of sorting among competing hypotheses were not addressed in this volume. The reader is directed to Walters (1986), Hilborn and Mangel (1998), and an extensive literature in the statistics area, as well as the area of optimal adaptive control in systems with unknown parameters.

The second area is the social arena. The types of organizational complexity raised by Westley (Chapter 13) and of political pathologies (Chapter 6) generate barriers for adoption of adaptive management in western, bureaucratic agencies. Adaptive management has been socially challenged through practices such as the self-serving interest of management agencies, self-interested career concerns and "greed" among scientific experts, and disinformation campaigns by opposing sides who exploit the uncertainty of multiple hypotheses for other gains (Walters 1997).

All of the conclusions presented provide a lurch or transformation in our understanding. Yet they also point out gaps in our knowledge. Suggestions of important avenues to explore to fill those gaps are presented in the next chapter. Before we attempt a synthesis, we present another set of discoveries in the final section, where we address and resolve paradoxes raised in Chapter 1.

Resolving Paradoxes of Sustainability

We began this volume with two paradoxes that provided key insights into the puzzle of sustainability. One involves the duality of success and failures in regional systems of humans and nature, and the second involves how scientific-based approaches appear to have created a competency trap.

Sustainable Regional Resource Development

Worldwide, people are struggling to manage large-scale resource systems. Many are failing, as shown by the numerous resource systems that exist in a constant or recurring state of crisis (Ludwig et al. 1993). In the Florida Everglades, for example, agricultural interests, environmentalists, and urban residents contest with one another for control over clean water (Light et al. 1995). In the U. S. Pacific Northwest, 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 decline (Jansson and Velner 1995). In these cases, resource management has taken a pathological form in which the complexity of the issues, institutional inertia, and uncertainty leads 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 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 on its continuation while simultaneously eroding the ecological support that it requires. This leads to a state in which ecological change is increasingly undesirable to the people dependent on the natural resource and 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.

When shifts occur between alternative states or conditions, it is usually signaled as a resource crisis. That is, a crisis occurs when an ecosystem behaves in a surprising manner or when observations of a system are qualitatively different from people's expectations of that system. Such surprises occur when variation in broad-scale processes (such as a hurricane or extreme drought) intersects with internal changes in an ecosystem due to human alteration. Examples include woody invasion of semiarid rangelands (Walker 1981), algae blooms in freshwater lakes (Carpenter and Leavitt 1991), and shifts in vegetation due to nutrient enrichment in the freshwater Everglades (Davis 1994). With each of these shifts in stability domains chronicled as crisis, understanding how and why people chose to react is key to managing for resilience.

When faced with shifting stability domains and corresponding crises, management options fall into one of three general classes of response. The first is to do nothing and wait to see if the system will return to some acceptable state while sacrificing lost benefits of the undesirable state. The second option is to actively manage the system and try to return the system to a desirable stability domain. The third option is to admit that the system is irreversibly changed, and hence the only strategy is to adapt to the new, altered system.

The resilience of the ecological system provides "insurance" within which managers can affordably fail and learn while applying policies and practices. The social equivalent of ecological resilience, or human adaptive capacity, resides in the ability to confront uncertainty and develop understanding of what contributes to loss of ecological resilience. Effective responses are those that identify sources of flexibility, as well as development of actions that are structured for learning and allow for the generation of novelty.

The explanation of the paradox of "the pathology of regional development and renewable resource management" is that natural systems have great resilience because of diversity within functions and across scales, and because humans can learn. Therefore, bad regional policy and management can typically be corrected, but at great and often increasing costs. The resilience is not infinite, and learning proceeds by costly lurches because of nonlinearities. Variability that maintains renewal capacity is the source of sustainable change, not the enemy of it. The key question for future work is how we can implement ways to expand human opportunity, sustain resilience, and facilitate human learning.

Developing New Expertise

Our book has stressed the "paradox of the expert," the tendency of experts to become rigid in their view and closed to potentially useful alternatives. Recent work in theoretical economics suggests some potentially useful speculation on this matter. Smith and Sorensen (2000) tell the following story, which can be adapted to experts in charge of managing an ecosystem. Imagine a series of experts, each of which must make sequential decisions about the true model of an ecosystem under scrutiny, all in the preordained order given by the research history on that ecosystem. Since the true model is an objective scientific matter, all these scientists would want to end up making the same decision about which model in a set of candidate models is the true model.

Smith and Sorensen study the problem of how rational individuals sequentially learn from the actions of others through a Bayesian approach of sorting among hypotheses rather than rejecting a single hypothesis. The main problem is the possible emergence of an incorrect herd or, in our context, settling on the wrong model. This unhappy result can occur even in the presence of a lot of information. This is so because each expert must condition his choice of model on his own research investigation, as well as the published work of all experts before him, but he cannot observe the rich, hidden investigative experiences of each of those previous experts. He can infer something about previous scientists' experiences by the way they write up their results and other indicators. These indicators provide information about the strength of the signal that each scientist received during his research as well as his observed reported beliefs about the true model.

This story is essentially an information cascade story. There has been a burst of research in economics on information cascade phenomena in social learning situations, with special emphasis on the possibility of incorrect herding on the wrong conclusion. Incorrect herding among scientists can lead to a situation where experts become rigid and closed to potentially fruitful ideas because, based on their collective investigative history, the right way has become established. Information cascade theory gives a potentially useful set of methods to make such vague notions more precise with the useful byproduct of giving us more precise methods of identifying situations where this potential danger looms large.

Notice that unlike the Brock and Durlauf (1999) peer-pressure scientist model, there are no external reference group pressure effects. Adding realistic peer-pressure effects in a group of experts referencing each other in their commonly learned culture, as well as realistic positional incentives where each expert tries to bolsters her credibility by reference to other experts, will strengthen the incorrect informational herd effect. A lesson that we learn from briefly considering the Brock and Durlauf, Smith and Sorensen (2000) theories applied to cultures of informational experts is how easy natural incentives can end up trapping a community of experts into a bad basin of attraction that is perversely resilient to the introduction of potentially useful alternative points of view. This observation might strengthen the case for building institutional frameworks where members of the lay public, even though they are not experts, interact in a mutually informative setting where each gets to speak her piece and each gets to question any expert in a nonintimidating, mutually open, and supportive framework. This process might act something like "simulated annealing," where the "shaking" effect might help keep the system from getting trapped in an inferior basin of attraction, but the emergence of potential consensus slows the shaking at an appropriate rate so that the best basin of attraction is found and eventually maintained.

In many cases of regional resource management, the trap of the expert is offset by tolerance of a diversity of ideas and hereticism. That is, in the cycles of surprise and renewal (Gunderson et al. 1995a; Berkes and Folke 1998; Johnson et al. 1999) that characterize large-scale resource systems, generally a small set of players help lead the social scientific dynamics in such a way that new ideas are injected, new policies are developed to correct failures of the past, and new ways of attempting to understand complex dynamics are developed. Those reformations are generally a result of past experience, research that somehow becomes integrated and crystallized at key times (Gunderson 1999a; Chapter 13).

The explanation of the paradox of "the trap of the expert" is that existing theory and practice for linked systems of nature, economies, and people are too partial and fragmented among ecology, economics, and social science. Well-intentioned recommendations of the expert therefore can often be so partial that they become ammunition for powerful vested interests to distort public information and policy. The key question for future work is how to develop and implement integrated understanding, policies, and actions among scientists, economic and public interest groups, and citizens so that a self-correcting market for knowledge and action develops.