Principles of Ecosystem Stewardship

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Resilience-Based Natural Resource Management in a Changing World

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Illustrated by Melissa C. Chapin

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Preface

The world is undergoing unprecedented changes in many of the factors that determine its fundamental properties and their influence on society. These changes include climate; the chemical composition of the atmosphere; the demands of a growing human population for food and fiber; and the mobility of organisms, industrial products, cultural perspectives, and information flows. The magnitude and widespread nature of these changes pose serious challenges in managing the ecosystem services on which society depends. Moreover, many of these changes are strongly influenced by human activities, so future patterns of change will continue to be influenced by society's choices and governance.

The purpose of this book is to provide a new framework for natural resource management—a framework based on stewardship of ecosystems for human well-being in a world dominated by uncertainty and change. The goal of ecosystem stewardship is to respond to and shape change in social-ecological systems in order to sustain the supply and opportunities for use of ecosystem services by society. The book links recent advances in the theory of resilience, sustainability, and vulnerability with practical issues of ecosystem management and governance. The book is aimed at advanced undergraduates and beginning graduate students of natural resource management as well as professional managers, community leaders, and policy makers with backgrounds in a wide array of disciplines, including ecology, policy studies, economics, sociology, and anthropology.

The first part of the book presents a conceptual framework for understanding the fundamental interactions and processes in social—ecological systems—systems in which people interact with their physical and biological environment. We explain how these systems respond to variability and change and discuss many of the ecological, economic, cultural, and institutional processes that contribute to these dynamics, enabling society to respond to and shape change. In the second section we apply this theory to specific types of social—ecological systems, showing how people adaptively manage resources and ecosystem services throughout the world. Finally we synthesize the lessons learned about resilience—based ecosystem stewardship as a strategy for responding to and shaping change in a rapidly changing world. Change brings both challenges and opportunities for managers, resource users, and policy makers to make informed decisions that enhance sustainability of our planet.

We owe a huge debt of gratitude to Buzz Holling who originated many of the central concepts that link resilience to ecosystem stewardship, as well as to several national and international programs that have developed these ideas and applied them to education and to the real-world issues faced by a rapidly changing planet. These include the Resilience Network, the Resilience Alliance, the International Geosphere-Biosphere Programme, the Millennium Ecosystem Assessment, the Stockholm Resilience Centre, the Beijer Institute, and the Resilience and Adaptation Program of the University of Alaska Fairbanks. Primary funding for the book came from the US National Science Foundation and the Swedish Research Council FORMAS program. In addition, many individuals contributed to the development of this book. We particularly thank our families, whose patience made the book possible, and our students, from whom we learned many of the concepts and applications presented in this book. In addition, we thank the following people for their constructively critical review of chapters in this book: Marty Anderies, Erik Anderson, Archana Bali, David Battisti, Harry Biggs, Oonsie Biggs, Steve Carpenter, Melissa Chapin, Johann Colding, Graeme Cumming, Bill Dietrich, Logan Egan, Thomas Elmqvist, Walter Falcon, Victor Galaz, Ted Gragson, Nancy Grimm, Lance Gunderson, Susan Herman, Buzz Holling, Jordan Lewis, Chanda Meek, Joanna Nelson, Evelyn Pinkerton, Ciara Raudsepp-Hearne, Marten Scheffer, Emily Springer, Samantha Staley, Will Steffen, Fred Swanson, Brian Walker, Karen Wang, and Oran Young. We particularly thank Steve Carpenter for his thoughtful comments on most of the chapters in this book.

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Part I
Conceptual Framework

1
A Framework for Understanding Change

F. Stuart Chapin, III, Carl Folke, and Gary P. Kofinas

Introduction

The world is undergoing unprecedented changes in many of the factors that determine both its fundamental properties and their influence on society. Throughout human history, people have interacted with and shaped ecosystems for social and economic development (Turner et al. 1990, Redman 1999, Jackson 2001, Diamond 2005). During the last 50 years, however, human activities have changed ecosystems more rapidly and extensively than at any comparable period of human history (Steffen et al. 2004, Foley et al. 2005, MEA 2005d; Plate 1). Earth's climate, for example, is now warmer than at any time in the last 500 (and probably the last 1,300) years (IPCC 2007a), in part because of atmospheric accumulation of carbon dioxide (CO_2) released by the burning of fossil fuels (Fig. 1.1). Agricultural development largely accounts for the accumulation of other trace gases that contribute to climate warming (see Chapter 12). As human population increases, in part due to improved disease prevention, the increased demand for food and natural resources has led to an expansion of agriculture, forestry, and other human activities, causing large-scale land-cover change and loss of habitats and biological diversity. About half the world's population now lives in cities and depends on connections with rural areas worldwide for food, water, and waste processing (see Chapter 13; Plate 2). In addition, increased human mobility is spreading plants, animals, diseases, industrial products, and cultural perspectives more rapidly than ever before. This increase in global mobility, coupled with increased connectivity through global markets and new forms of communication, links the world's economies and cultures, so decisions in one place often have international consequences.

This **globalization** of economy, culture, and ecology is important because it modifies the **life-support system** of the planet (Odum 1989), i.e., the capacity of the planet to meet the needs of all organisms, including people. The dramatic increase in the extinction rate of species (100- to 1,000-fold in the last two centuries) indicates that global changes have been catastrophic for many species, although some species,

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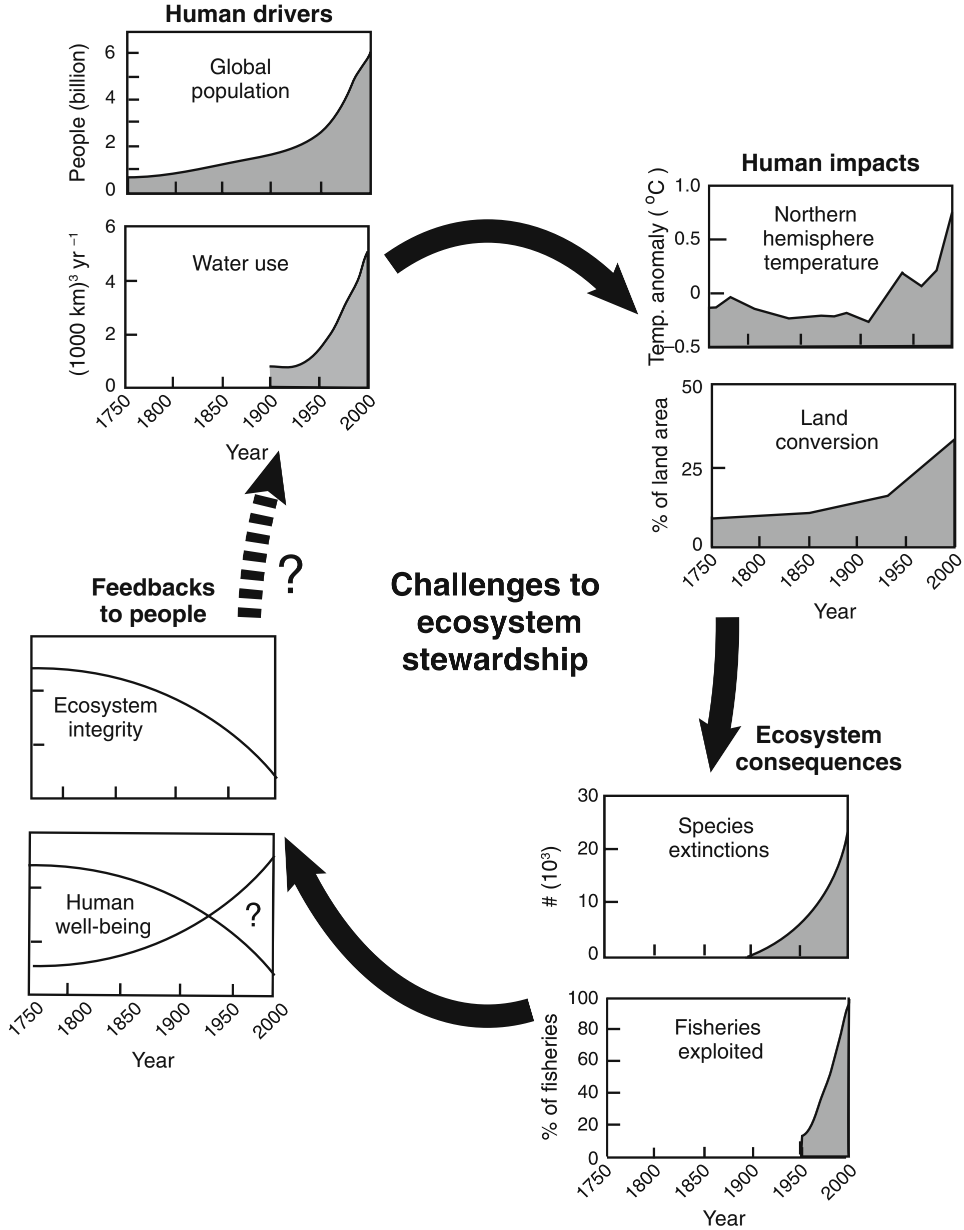


FIGURE 1.1. Challenges to research stewardship. Changes in human population and resource consumption alter climate and land cover, which have important ecosystem consequences such as species extinctions and overexploitation of fisheries. These changes reduce ecosystem integrity and have regionally variable effects on human well-being, which feeds back to further changes in human drivers. Panel inserts redrawn from Steffen et al. (2004).

especially invasive species and some disease organisms, have benefited and expanded their ranges. Human society has both benefited and suffered from global changes, with increased food production, increased income and living standards (in parts of the world), improved treatment of many diseases, and longer life expectancy being offset by deterioration in

ecosystem services, the benefits that society receives from ecosystems. More than half of the ecosystem services on which society depends for survival and a good life have been degraded—not deliberately, but inadvertently as people seek to meet their material desires and needs (MEA 2005d). Change creates both challenges and opportunities. People have amply demonstrated their capacity to alter the life-support system of the planet. In this book we argue that, with appropriate stewardship, this human capacity can be mobilized to not only repair but also enhance the capacity of Earth's life-support system to support societal development.

The unique feature of the changes described above is that they are **directional**. In other words, they show a persistent trend over time (Fig. 1.1). Many of these trends have become more pronounced since the mid-twentieth century and will probably continue or accelerate in the coming decades, even if society takes concerted actions to reduce some rates of change. This situation creates a dilemma in planning for the future because we cannot assume that the future world will behave as we have known it in the past or that our past experience provides an adequate basis to plan for the future. This issue is especially acute for **sustainable management** of natural resources. It is no longer possible to manage systems so they will remain the same as in the recent past, which has traditionally been the reference point for resource managers and conservationists. We must adopt a more flexible approach to managing resources—management to sustain the *functional* properties of systems that are important to society under conditions where the system itself is constantly changing. Managing resources to foster **resilience**—to respond to and shape change in ways that both sustain and develop the same fundamental function, structure, identity, and feedbacks—seems crucial to the future of humanity and the Earth System. **Resilience-based ecosystem stewardship** is a fundamental shift from steady-state resource management, which attempted to reduce variability and prevent change, rather than to respond to and shape change in ways that benefit society (Table 1.1). We emphasize *resilience*, a concept that embraces change as a basic feature of the way the world works and develops, and therefore is especially appropriate at times when changes are a prominent feature of the system. We address *ecosystems* that provide a suite of ecosystem services rather than a

Table 1.1. Contrasts between steady-state resource management, ecosystem management, and resilience-based ecosystem stewardship.

Steady-state resource management	Ecosystem management	Resilience-based ecosystem stewardship
Reference state: historic condition	Historic condition	Trajectory of change
Manage for a single resource or species	Manage for multiple ecosystem services	Manage for fundamental social–ecological properties
Single equilibrium state whose properties can be sustained	Multiple potential states	Multiple potential states
Reduce variability	Accept historical range of variability	Foster variability and diversity
Prevent natural disturbances	Accept natural disturbances	Foster disturbances that sustain social–ecological properties
People use ecosystems	People are part of the social–ecological system	People have responsibility to sustain future options
Managers define the primary use of the managed system	Multiple stakeholders work with managers to define goals	Multiple stakeholders work with managers to define goals
Maximize sustained yield and economic efficiency	Manage for multiple uses despite reduced efficiency	Maximize flexibility of future options
Management structure protects current management goals	Management goals respond to changing human values	Management responds to and shapes human values

single resource such as fish or trees. We focus on *stewardship*, which recognizes managers as an integral component of the system that they manage. Stewardship also implies a sense of responsibility for the state of the system of which we are a part (Leopold 1949). The challenge is to anticipate change and shape it for sustainability in a manner that does not lead to loss of future options (Folke et al. 2003). Ecosystem stewardship recognizes that society's use of resources must be compatible with the capacity of ecosystems to provide services, which, in turn, is constrained by the life-support system of the planet (Fig. 1.2).

This chapter introduces a framework for understanding and managing resources in a world where persistent directional changes are becoming more pronounced. We first present a framework for studying change—one that integrates the physical, ecological, and social dimensions of change and their interactions. We then describe the general properties of systems that magnify or resist change. Finally we discuss general approaches to sustaining desirable system properties in a directionally changing world and present a road map to the remaining chapters, which address these issues in greater depth.

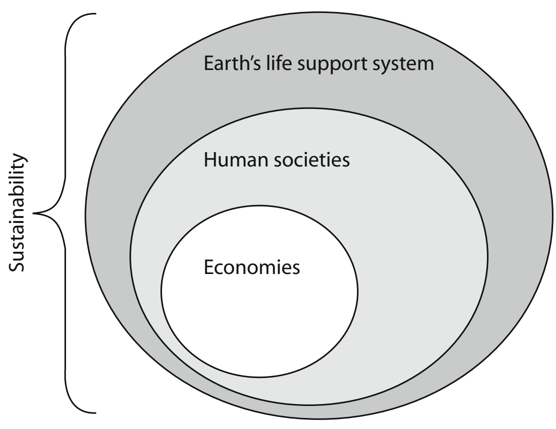


FIGURE 1.2. Social–ecological sustainability requires that society's economy and other human activities *not* exceed the capacity of ecosystems to provide services, which, in turn, is constrained by the planet's life-support system. Redrawn from Fischer et al. (2007).

An Integrated Social–Ecological Framework

Linking Physical, Ecological, and Social Processes

Changes in the Earth System are highly interconnected. None of the changes mentioned above is purely physical, ecological, or social. Therefore understanding current and future change requires a broad interdisciplinary framework that draws on the concepts and approaches of many natural and social sciences. We must understand the world, region, or community as a **social–ecological system** (also termed a coupled human–environment system) in which people depend on resources and services provided by ecosystems, and ecosystem dynamics are influenced, to varying degrees, by human activities (Berkes et al. 2003, Turner et al. 2003, Steffen et al. 2004). Although the relative importance of social and ecological processes may vary from forests to farms to cities, the functioning of each of these systems, and of the larger regional system in which they are embedded, is strongly influenced by physical, ecological, economic, and cultural factors. They are, therefore, best viewed, not as ecological *or* social systems, but as social–ecological systems that reflect the interactions of physical, ecological, and social processes.

Forests, for example, are sometimes managed as ecological systems in which the nitrogen inputs from acid rain or the economic influences on timber demand are considered **exogenous factors** (i.e., factors external to the system being managed) and therefore are not incorporated into management planning. Production of lumber or paper, on the other hand, is often managed as an economic system that must balance the supply and costs of timber inputs against the demand for and profits from products without considering ecological influences on forest production. Finally, local planners make decisions about school budgets and the zoning for development and recreation, based on assumptions about regional water supply, which depends on forest cover, and economic projections, which are influenced by the economic activity of forest industries. The system and its components are more vulnerable to unexpected changes (**surprises**) when each subsystem is managed in isolation. These surprises might include harvest restrictions to protect an endangered species, development of inexpensive lumber supplies on another continent, or expansion of recreational demand for forest use by nearby urban residents. More informed decisions are likely to emerge from integrated approaches that recognize the interdependencies of regional components and account for uncertainty in future conditions (Ludwig et al. 2001). Resource stewardship policies must therefore be ecologically, economically, and culturally viable, if they are to provide sustainable solutions.

In studying the response of social–ecological systems to directional change, we pay particular attention to the processes that link ecological and social components (Fig. 1.3). The environment affects people through both

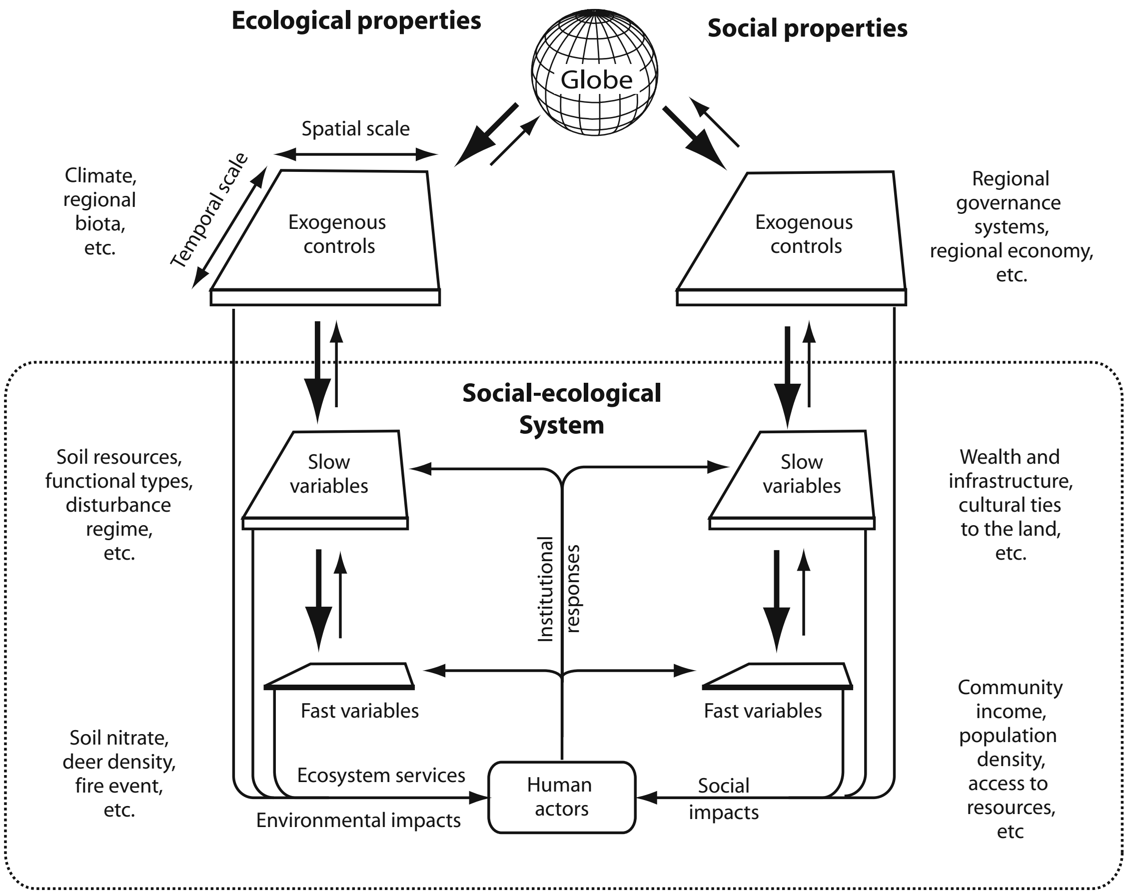


FIGURE 1.3. Diagram of a social–ecological system (the rectangle) that is affected by ecological (left-hand side) and social properties (right-hand side). In both subsystems there is a spectrum of controls that operate across a range of temporal and spatial scales. At the regional scale exogenous controls respond to global trends and affect slow variables at the scale of management, which, in turn, influence fast variables that change more quickly. When changes in fast variables persist over long time periods and large areas, these effects cumulatively propagate upward to affect slow variables, regional controls, and eventually the entire globe. Changes in both slow and fast variables influence environmental impacts, ecosystem services, and social impacts, which, together, are the factors that directly affect the well-being of human actors, who modify both ecological and social systems through a variety of institutions. Modified from Chapin et al. (2006a).

direct environmental events such as floods and droughts and ecosystem services such as food and water quality (see Chapter 2). Many economic, political, and cultural processes also shape human responses to the physical and biological environment (see Chapter 3). Human actors (both individuals and groups) in turn affect their ecological environment through a complex web of social processes (see Chapter 4). Together these linkages between social and ecological processes structure the dynamics of social–ecological systems (see Chapter 5).

The concept that society and nature depend on one another is not new. It was well recognized by ancient Greek philosophers (Boudouris and Kalimtzis 1999); economists concerned with the environmental constraints on human population growth (Malthus 1798); geographers and anthropologists seeking to understand global patterns of land use and culture (Rappaport 1967, Butzer 1980); and ecologists and conservationists concerned with human impacts on the environment (Leopold 1949, Carson 1962, Odum 1989). The complexity and importance of social–ecological interactions has led many natural and social science disciplines to address components of the interaction to both improve understanding and solve problems. For example, resource management considers the actions that agencies or individuals take to sustain natural resources, but typically pays less attention to the interactions among interest groups that influence how management policies develop or how the public will respond to management. Similarly, environmental policy analysis addresses the potential interactions of environmental policies developed by different organizations, but typically pays less attention to potential social or ecological **thresholds** (critical levels of drivers or state variables that, when crossed, trigger abrupt changes or **regime shifts**) that determine the long-term effectiveness of these policies. The breadth of approaches provides a wealth of tools for studying integrated social–ecological systems. Disciplinary differences in vocabulary, methodology, and standards of what constitutes academic rigor can, however, create barriers to communication (Box 1.1; Wilson 1998). The increasing recognition that human actions are threatening Earth's life-support system has recently generated a sense of urgency in addressing social–ecological systems in a more integrated fashion (Berkes et al. 2003, Clark and Dickson 2003, MEA 2005d). This requires a system perspective that integrates social and ecological processes and is flexible enough to accommodate the breadth of potential human actions and responses.

Box 1.1. Challenges to Navigating Social–Ecological Barriers and Bridges.

The heading of this box combines the titles of two seminal books on integrated social–ecological systems ("Barriers and Bridges" and "Navigating Social Ecological Systems"; Gunderson et al. 1995, Berkes et al. 2003). These titles capture the essence of the challenges in integrating natural and social sciences. In this book we adopt the following conventions in addressing two important challenges in this **transdisciplinary** integration (i.e., integration that transcends traditional disciplines to formulate problems in new ways).

The same word often means different things.

1. To a sociologist, **adaptation** means the behavioral adjustment by individuals to their environment. To an ecologist it means the genetic changes in a population to adjust to their environment (in contrast to acclimation, which entails physiological or behavioral adjustment by individuals). To an anthropologist adaptation means the cultural adjustment to environment, without specifying its genetic or behavioral basis. *In this book we use **adaptation** in its most general sense (adjustment to change in environment).*

2. To an engineer or ecologist describing systems with a single equilibrium, **resilience** is the time required for a system to return to equilibrium after a perturbation. To someone describing systems with multiple stable states, resilience is capacity of the system to absorb a spectrum of shocks or perturbations and still retain and further develop the same fundamental structure, functioning, and feedbacks. *We use* ***resilience*** *in the latter sense*.
3. Natural scientists describe feedbacks as being **positive** or **negative** to denote whether they are amplifying or stabilizing, respectively. These words are often used in the social sciences (and in common usage) to mean good or bad. The terminology is especially confusing for social–ecological systems, because negative feedbacks are often socially desirable (= “good”) and positive feedbacks socially undesirable (= “bad”). *We therefore avoid these terms and talk about* ***amplifying*** *or* ***stabilizing feedbacks***.
4. Words that represent important concepts in one discipline may be meaningless or viewed as jargon in another (e.g., **postmodern**, **state factor**). *We define each technical word the first time it is used and use only those technical terms that are essential to convey ideas effectively*.

Approaches that are viewed as “good science” in one discipline may be viewed with skepticism in another.

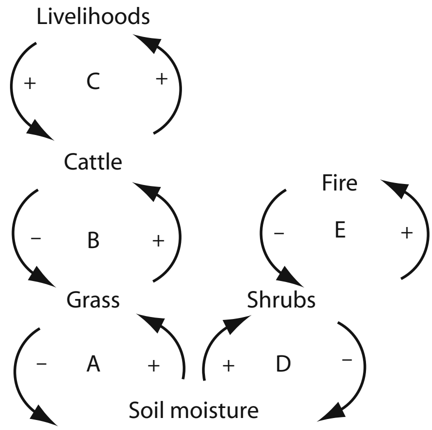
1. Some natural scientists use **systems models** to describe (either quantitatively or qualitatively) the interactions among components of a system (such as a social–ecological system). Some social scientists view this as an inappropriate tool to study systems with a strong human element because it seems too deterministic to describe human actions. *We use* ***complex adaptive systems*** *as a framework to study social–ecological systems because it enables us to study the integrated nature of the system but recognizes legacies of past events and the path dependence of human agency as fundamental properties of the model*.
2. Some natural scientists rely largely on quantitative data as evidence to test a hypothesis, whereas some social scientists make extensive use of qualitative descriptions of patterns that are less amenable to quantification. *We consider both approaches essential to understanding the complex dynamics of social–ecological systems*.

A Systems Perspective

Systems theory provides a conceptual framework to understand the dynamics of integrated systems. A social–ecological system consists of physical components, including soil, water, and rocks; organisms (plants, microbes, and animals—including people); and the products of human activities, such as food, money, credit, computers, buildings, and pollution. A social–ecological system is like a box or a board game, with explicit boundaries and rules, enabling us to quantify the amount of materials (for example, carbon, people, or money) in the system and the factors that influence their flows into, through, and out of the system.

Social–ecological systems can be defined at many scales, ranging from a single household or community garden to the entire planet. Systems are defined to include those components and interactions that a person most wants to understand. The size, shape, and boundaries of a social–ecological system therefore depend entirely on the problem addressed and the objectives of study. A watershed that includes all the land draining into a lake, for example, is an appropriate system for studying the controls over pollution of the lake. A farm, city, water-management district, state, or country might be a logical unit for studying the effects of government policies. A community, nation, or the globe might be an appropriate unit for studying barter and commerce. A neighborhood, community, or multinational region might be a logical unit for studying cultural change. Defining the most appropriate unit of analysis is challenging because key ecological and social processes often differ in scale and logical boundaries (for example, watersheds and water-management districts; Ostrom 1990, Young 1994). Most social–ecological systems are **open systems**, in the sense that there are flows of materials, organisms, and information into and out of the system. We therefore cannot ignore processes occurring outside our defined system of analysis, for example, the movement of food and wastes across city boundaries.

Social–ecological processes are the interconnections among components of a system. These may be primarily ecological (for example, plant production, decomposition, wildlife migration), socioeconomic (manufacturing, education, fostering of trust among social groups), or a mix of ecological and social processes (plowing, hunting, polluting). The interactions among multiple processes govern the dynamics of social–ecological systems. Two types of interactions among components (amplifying and stabilizing feedbacks) are especially important in defining the internal dynamics of the system because they lead to predictable outcomes (DeAngelis and Post 1991, Chapin et al. 1996). **Amplifying feedbacks** (termed positive feedbacks in the systems literature) augment changes in process rates and tend to destabilize the system (Box 1.2). They occur when two interacting components cause one another to change in the same direction (both components increase or both decrease; Fig. 1.4). A disease epidemic occurs, for example, when a disease infects susceptible hosts, which produce more disease organisms, which infect more hosts, etc., until some other set of interactions constrains this spiral of disease increase. Overfishing can also lead to an amplifying feedback, when the decline in fish stocks gives rise to price supports that enable fishermen to maintain or increase fishing pressure despite smaller catches, leading to a downward spiral of fish abundance. Other examples of amplifying feedbacks include



Process		Nature of feedback
Resource uptake	A or D	Stabilizing
Competition	A+D	Stabilizing
Herbivory	B	Stabilizing
Resource exploitation	C	Amplifying
Disturbance cycle	E	Stabilizing

FIGURE 1.4. Examples of linked amplifying and stabilizing feedbacks in social–ecological systems. Arrows show whether one species, resource, or condition has a positive or a negative effect on another. The feedback between two species is *stabilizing* when the arrows have opposite sign (for example, species 1 has a positive effect on species 2, but species 2 has a negative effect on species 1). The feedback is amplifying, when both species affect one another in the same direction (for example, more cattle providing more profit, which motivates people to raise more cattle; feedback loop C in the diagram).

population growth, erosion of cultural integrity in developing nations, and proliferation of nuclear weapons.

Stabilizing feedbacks (termed negative feedbacks in the systems literature) tend to reduce fluctuations in process rates, although, if extreme, they can induce chaotic fluctuations. Stabilizing feedbacks occur when two interacting components cause one another to change in opposite directions (Fig. 1.4). For example, grazing by cattle reduces the biomass of forage grasses, whereas the grass has a positive effect on cattle production. Any increase in density of cattle reduces grass biomass, which then constrains the food available to cattle, thereby stabilizing the sustainable densities of both grass and cattle at intermediate levels. Other examples of stabilizing feedbacks include prices of goods in a competitive market and nutrient supply to plants in a forest. One of the keys to sustainability is to foster stabilizing feedbacks and constrain amplifying feedbacks that might otherwise push the system toward some new state. Conversely, if the current state is socially undesirable, for example, at an abandoned mine site, carefully selected amplifying feedbacks may shift the system to a preferred new state.

Box 1.2. Dynamics of Temporal Change

The stability and dynamics of a system depend on the balance of amplifying and stabilizing feedbacks and types and frequencies of perturbations. The strength and nature of feedbacks largely govern the way a system responds to change. A system without strong feedbacks shows **chaotic behavior** in response to a random perturbation. Chaotic behavior is unpredictable and depends entirely on the nature of the perturbation. The behavior of a ball on a surface provides a useful analogy (Fig. 1.5; Holling and Gunderson 2002, Folke et al. 2004). The location of the ball represents the state of a system as a function of some variable such as water availability. In a chaotic system without feedbacks, the surface is flat, and we cannot predict changes in the state (i.e., location) of the system in response to a random perturbation (Fig. 1.5a). This system structure is analogous to theories that important decisions can be described in terms of the potential solutions and actors that happen to be present at key moments (garbage-can politics; Cohen et al. 1972, Olsen 2001).

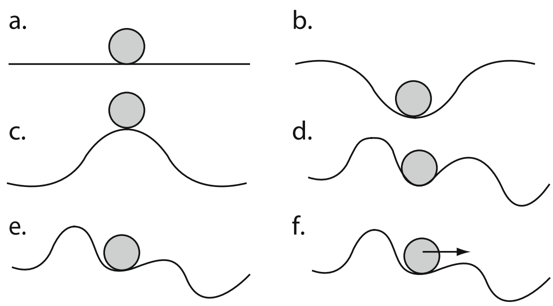


FIGURE 1.5. The location of the ball represents the state of a system in relationship to some ecological or social variable (e.g., water availability, as represented by the position along the horizontal axis). Changes in the state of the system in response to a perturbation depend on the nature of system feedbacks (illustrated as the shape of the surface). The likelihood that the system will change its state (location along the line) differs if there are (**a**) no feedbacks, (**b**) stabilizing feedbacks, (**c**) amplifying feedbacks, (**d**) alternative stable states, (**d**–**e**) changes in the internal feedback structure (complex adaptive system), and (**e**–**f**) response of a complex adaptive system to persistent directional changes in a control variable.

A system dominated by *stabilizing feedbacks* tends to be stable because the interactions occurring within the system minimize the changes in the system in response to perturbations. Using our analogy, stabilizing feedbacks create a bowl-like depression in the surface so the ball tends to return to the same location after a random perturbation (Fig. 1.5b). The resilience of the system, in this cartoon, is the likelihood that it will remain in the same state despite perturbations. This analogy characterizes the perspective of a balanced view of nature, in which there is a **carrying capacity** (maximum quantity) of fish, game, or trees that the environment can support, allowing managers to regulate harvest to achieve a **maximum sustained yield**. This view is often based on considerable depth of biological understanding but is incomplete (Holling and Gunderson 2002).

A system dominated by *amplifying feedbacks* tends to be unstable because the initial change is amplified by interactions occurring within the system. Amplifying feedbacks tend to push the system toward some new state by making the depressions less deep or creating elevated areas on the surface (Fig. 1.5c). This analogy characterizes the view that small is beautiful and that any technology is bad because it causes change. There are certainly many examples where technology has led to unfavorable outcomes, but this worldview, like the others, is incomplete (Holling and Gunderson 2002).

Many systems can be characterized by **alternative stable states**, each of which is plausible in a given environment. Neighborhoods in US cities, for example, are likely to be either residential or industrial but unlikely to be an even mix of the two. In the surface analogy, alternative stable states represent multiple depressions in the surface (Fig. 1.5d). A system is likely to return to its original state (=depression) after a small perturbation, but a larger disturbance might increase the likelihood that it will shift to some alternative state. In other words, the system exhibits a nonlinear response to the perturbation and shifts to a new state if some **threshold** is exceeded. There may also be pathways of system development, such as the stages of forest succession, in which the internal dynamics of the system cause it to move readily from one state to another. Some of these depressions may be deep and represent irreversible traps. Others may be shallow, so the system readily shifts from one state to another through time. This worldview incorporates components of all the previous perspectives but is still incomplete.

The previous cartoons of nature imply that the stability landscape is static. However, each transition influences the internal dynamics of a complex adaptive system and therefore the probability of subsequent transitions, so the shape of the surface is constantly changing (Fig. 1.5e). Reductions in Atlantic cod populations due to overfishing, for example, increased pressures for establishment of aquaculture and charter fishing businesses, which then made it less likely that industrial-scale cod fishing would return to the North Atlantic. This analogy of a stability landscape that is constantly evolving suggests that precise predictions of the future state of the system are impossible and focuses attention on understanding the dynamics of change as a basis for stewardship (Gunderson and Holling 2002).

Now imagine that rather than having a random perturbation in some important state variable like water availability, this parameter changes directionally. This element of directionality increases the likelihood that the system will change in a specific direction after perturbation (Fig. 1.5f). The stronger and more persistent the directional changes in exogenous control variables, the more likely it is that new states will differ from those that we have known in the past. This represents our concept of system response to a directionally changing environment.

Issues of Scale: Exogenous, Slow, and Fast Variables

Changes in the state of a system depend on variables that change slowly but strongly influence internal dynamics. Social–ecological systems respond to a spectrum of controls that operate across a range of temporal and spatial scales. These can be roughly grouped as exogenous controls, slow variables, and fast variables (Fig. 1.3). We describe these first for ecological subsystems, then consider their social counterparts.

Exogenous controls are factors such as regional climate or biota that strongly shape the properties of continents and nations. They remain relatively constant over long time periods (e.g., a century) and across broad regions and are not strongly influenced by short-term, small-scale dynamics of a single forest stand or lake. At the scale of an ecosystem or watershed, there are a few **critical slow variables**, i.e., variables that strongly influence social–ecological systems but remain relatively constant over years to decades despite interannual variation in weather, grazing, and other factors, because they are buffered by stabilizing feedbacks that prevent rapid change (Chapin et al. 1996, Carpenter and Turner 2000). Soil organic matter, for example, retains pulses of nutrients from autumn leaf fall, crop residues, or windstorms; retains water and nutrients; and releases these resources which are then absorbed by plants; the quantity of soil organic matter is buffered by feedbacks related to plant growth and litter production. Critical slow variables include presence of particular **functional types** of plants and animals (e.g., evergreen trees or herbivorous mammals); **disturbance regime** (properties such as frequency, severity, and size that characterize typical disturbances); and the capacity of soils or sediments to supply water and nutrients. Slow variables in ecosystems, in turn, govern **fast variables** at the same spatial scale (e.g., deer or aphid density, individual fire events) that respond sensitively to daily, seasonal, and interannual variation in weather and other factors. When aggregated to regional or global scales, changes that occur in ecosystems, for example, those mediated by human activities, can modify the environment to such an extent that even regional controls such as climate and regional biota that were once considered constant parameters are now directionally changing at decade-to-century time scales (Foley et al. 2005). Regardless of the causes, persistent directional changes in broad regional controls, such as climate and biodiversity, inevitably cause directional changes in critical slow variables and therefore the structure and dynamics of ecosystems, including the fast variables. The exogenous and slow variables are critical to long-term sustainability, although most management and public attention focus on fast variables, whose dynamics are more visible.

Analogous to the ecological subsystem, the social subsystem can be viewed as composed of exogenous controls, critical slow variables, and fast variables (Straussfogel 1997). These consist of vertically nested relationships, ranging from global to local, and linked by cross-scale interactions (Ostrom 1999a, Young 2002b, Adger et al. 2005). At the sub-global scale a predominant history, culture, economy, and governance system often characterize broad regions or nation states such as Europe or sub-Saharan Africa (Chase-Dunn 2000). These exogenous social controls tend to be less sensitive to interannual variation in stock-market prices and technological change than are the internal dynamics of local social–ecological systems; the exogenous controls constrain local options. This asymmetry between regional and local controls occurs in part because of asymmetric power relationships between national and local entities and in part because changes in a small locality must be very strong to substantially modify the dynamics of large regions. Regional controls sometimes persist for a long time and change primarily in response to changes that are global in extent (e.g., globalization of markets and finance institutions), but at other times change can occur quickly, as with the collapse of the Soviet Union in the 1990s or the globalization of markets and information (Young et al. 2006). As in the biophysical system, a few slow variables (e.g., wealth and infrastructure; property-and-use rights; and cultural ties to the land) are constrained by regional controls and interact with one another to shape fast variables like community income or population density. Both slow and fast social variables can have major effects on ecological processes (Costanza and Folke 1996, Holling and Sanderson 1996).

Systems differ in their sensitivity to different types of changes or the range of conditions over which the change occurs. The !Kung San of the Kalahari Desert will be much more sensitive than people of a rainforest to a 10-cm increase in annual rainfall because it represents a doubling of rainfall rather than a 5% increase. Regions also differ in their sensitivity to introduction of new biota (spruce bark beetle, zebra mussel, or West Nile virus), new economic pressures (development of aquaculture, shifting of car manufacture to Asia, collapse of the stock market), or new cultural values. There are typically relatively few (often only three to five) slow variables that are critical in understanding the current dynamics of a specific system (Carpenter et al. 2002), so management designed to reduce sensitivity to directional changes in slow variables is not an impossible task. The identity of critical control variables may change over time, however, requiring continual reassessment of our understanding of the social–ecological system. The key challenge, requiring collaborative research by managers and natural and social scientists, is to identify the critical slow variables and their likely changes over time.

Incorporating Scale, Human Agency, and Uncertainty into Dynamic Systems

Cross-scale linkages are processes that connect the dynamics of a system to events occurring at other times or places (see Chapter 5). Changes in the human population of a region, for example, may be influenced by the wealth and labor needs of individual families (fine scale), by national policies related to birth control (focal scale), and by global inequalities in living standards that influence immigration (large scale). Events that occur at each scale typically influence events at other scales. The universal importance of cross-scale linkages in social–ecological systems makes it important to study them at multiple temporal and spatial scales, because different insights and answers emerge at each scale (Berkes et al. 2003).

Legacies are past events that have large effects on subsequent dynamics of social–ecological systems. This generates a **path dependence** that links current dynamics to past events and lays the foundation for future changes (North 1990). Legacies include the impact of plowing on soils of a regenerating forest, the impact of the Depression in the 1930s on economic decisions made by households 40 years later, and the continuation of subsistence activities by indigenous people who move from villages to cities. Because of path dependence, the current dynamics of a system always depend on both current conditions and the history of prior events. Consequently, different trajectories can occur at different times or places, even if the initial conditions were the same. Path dependence is absolutely critical to management, because it implies that human actions taken today, whether constructive or destructive, can influence the future state of the system. Good management can make a difference!

Human agency (the capacity of humans to make choices that affect the system) is one of the most important sources of path dependence. Human decisions depend on both past events (legacy effects) and the plans that people make for the future (**reflexive behavior**). The strong path dependence of social–ecological systems is typical of a general class of systems known as **complex adaptive systems**. These are systems whose components interact in ways that cause the system to adjust (i.e., “adapt”) in response to changes in conditions. This is not black magic, but a consequence of interactions and feedbacks. Some of the most frequent failures in resource management occur because managers and resource users fail to understand the principles by which complex adaptive systems function. It is therefore important to understand their dynamics. Understanding these dynamics also provides insights into ways that managers can achieve desirable outcomes in a system that is responding simultaneously to management actions and to persistent directional changes in exogenous controls.

Whenever system components with different properties interact spontaneously with one another, some components persist and others disappear (i.e., the system adapts; Levin 1999; Box 1.2). In social–ecological systems, for example, organisms compete or eat one another, causing some species to become more common and others to disappear. Similarly, purchasing or competitive relationships among businesses cause some firms to persist and others to fail. Those components that interact through stabilizing feedbacks are most likely to persist. This **self-organization** of components linked by stabilizing feedbacks occurs spontaneously without any grand design. It causes complex adaptive systems to be relatively **stable** (tend to maintain their properties over time; DeAngelis and Post 1991, Levin 1999). This **self-regulation** simplifies management challenges in many respects. A complex adaptive system like a forest, for example, tends to "take care of itself." This differs from a designed structure like a car, whose components do not interact spontaneously and where maintenance must be continually applied just to keep the car in the same condition (Levin 1999).

If conditions change enough to alter the interactions among system components, the system adapts to the new conditions, hence the term complex *adaptive* system (Levin 1998). The new balance of system components, in turn, alters the way in which the system responds to perturbations (path dependence), creating **alternative stable states**, each of which could exist in a given environment (see Chapter 5). Given that exogenous variables are always changing on all time scales, social–ecological systems are constantly adjusting and changing. Consequently, it is virtually impossible to manage a complex adaptive system to attain constant performance, such as the constant production of a given timber species. System properties are most likely to change if there are directional changes in exogenous controls. The stronger and more persistent the directional changes in control variables, the more likely it is that a threshold will be exceeded, leading to a new state.

If a threshold is exceeded, and the system changes radically, new interactions and feedbacks assume greater importance, and some components of the previous system may disappear. If a region shifts from a mining to a tourist economy, for example, the community may become more concerned about funding for education and regulations that assure clean water. The regime shifts that occur as the system changes state also depend on the past state of the system (path dependence). The presence of a charismatic leader or nongovernmental organization (NGO), for example, can be critical in determining whether large cattle ranches are converted to conservation easements or subdivisions when rising land values and taxes make ranching unprofitable.

These simple generalizations about complex adaptive systems have profound implications for resource stewardship: (1) Social and ecological components of a social–ecological system always interact and cannot be managed in isolation from one another. (2) Changes in social or ecological controls inevitably alter social–ecological systems regardless of management efforts to prevent change. (3) Historical events and human actions, including management, can strongly influence the pathway of change. (4) The thresholds and nonlinear dynamics associated with path dependence, compounded by lack of information and human volition, constrain our capacity to predict future change. Resource management and policy decisions must, therefore, always be made in an environment of **uncertainty** (Ludwig et al. 1993, Carpenter et al. 2006a).

Adaptive Cycles

The long-term stability of systems depends on changes that occur during critical phases of cycles of long-term change. All systems experience disturbances such as fire, war, recession, change in leadership philosophy, or closure of manufacturing plants that cause large rapid changes in key system properties. Such disturbances have qualitatively different effects on social–ecological systems than do short-term variability and gradual change. **Adaptive cycles** provide a framework for describing the role of disturbance in social–ecological systems (Holling 1986). They are cycles of system disruption, reorganization, and renewal. In an adaptive cycle, a system can be disrupted by disturbance and either regenerate to a similar state or be transformed to some new state (Fig. 1.6a; Holling 1986, Walker et al. 2004). Adaptive cycles exhibit several recognizable phases. The cycle may be initiated by a disturbance such as a stand-replacing wildfire that causes a rapid change in most properties of the system. Trees die, productivity decreases, runoff to streams increases, and public faith in fire management is shattered. This **release phase** occurs in hours to days and radically reduces the structural complexity of the system. Other factors that might trigger release include

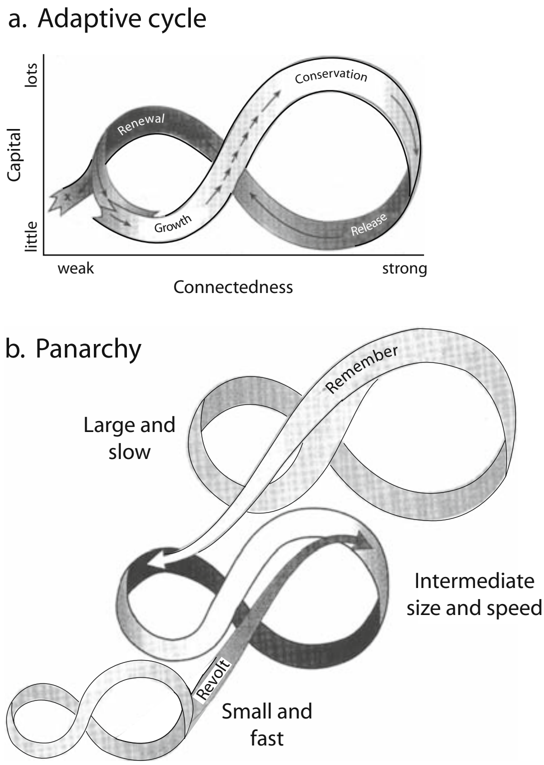


FIGURE 1.6. (**a**) Adaptive cycle and (**b**) cross-scale linkages among adaptive cycles (panarchy) in a social–ecological system. At any given scale, a system often goes through adaptive cycles of release (collapse), renewal (reorganization), growth, and conservation (steady state). These adaptive cycles of change can occur at multiple levels of organizations, such as individuals, communities, watersheds, and regions. These adaptive cycles interact forming a panarchy. For example, dynamics at larger scales (e.g., migration dynamics or wealth) provide legacies, context, and constraints that shape patterns of renewal (system memory). Dynamics at finer scales (e.g., insect population dynamics, household structure) may trigger release (revolt; e.g., insect outbreak). Redrawn from Holling and Gunderson (2002) and Holling et al. (2002b).

threshold response to phosphorus loading of a lake, collapse of the local or regional economy, or a transition from traditional to intensive agriculture. Following release, there is a relatively brief (months to years) **renewal phase**. For example, after forest disturbance, seedlings establish and new policies for managing the forest may be adopted. Many things can happen during renewal: The species and policies that establish might be similar to those present before the fire. It is also a time, however, when there is relatively little resistance to the establishment of a new suite of species or policies that emerge from the surrounding landscape (see Fig. 2.4). These innovations may lead to a system that is quite different from the prefire system, i.e., a **regime shift**. After this brief window of opportunity for change, the forest goes through a **growth phase** over several decades, when environmental resources are incorporated into living organisms, and policies become regularized. The nature of the regenerating forest system is largely determined by the species and regulations that established during renewal. During the growth phase, the forest is relatively insensitive to potential agents of disturbance. The high moisture content and low biomass of early successional trees, for example, make regenerating forests relatively nonflammable. Constant changes in the nature of the forest cause both managers and the public to accept changing conditions and regulations as a reasonable pattern. As the forest develops into the steady-state **conservation phase**, the interactions among components of the system become more specialized and complex. Light and nutrients decline in availability, for example, leading to specialization among plants to use different light environments and different fungal associations (**mycorrhizae**) to acquire nutrients. Similarly, in the policy realm, the relatively constant state of the forest leads to management rules that are aimed at maintaining this constancy to provide predictable patterns of recreation, hunting, and forest harvest. Due to the increased interconnectedness among these social and ecological variables, the forest becomes more vulnerable to any factor that might disrupt this balance, including fire, drought, changes in management goals, or a shift in the local economy. Large changes in any of these factors could trigger a new release in the adaptive cycle.

Many human organizations also exhibit cyclic patterns of change. A business or NGO, for example, may be founded in response to a perceived opportunity for profit or social reform. If successful, it grows amidst constant adjustment to changes in personnel and activities. Eventually it reaches a relatively stable size, at which time the internal structure and operating procedures are regularized, making it less flexible to respond to changes in the economic or social climate. When conditions change, the business or NGO may either enter a new period of adjustment (growth) or decline (release), followed by potential renewal or collapse.

Perhaps the most surprising thing about adaptive cycles is that the sequence of phases (release, renewal, growth, and conservation) can be used as a way of thinking about many types of social-ecological systems, including lakes, businesses, governments, national economies, and cultures, although the sequence of phases is not always the same (Gunderson et al. 1995). Clearly the specific mechanisms underlying cycles in these different systems must be quite different. One of the unsolved challenges in understanding social–ecological systems is to determine the general system properties and mechanisms that underlie the apparent similarities in cyclic patterns of different types of systems and to clarify the differences. The specific mechanisms of adaptive cycles in different types of systems are described in many of the following chapters.

One of the most important management lessons to emerge from studies of adaptive cycles is that social–ecological systems are typically most **vulnerable** (likely to change to a new state in response to a stress or disturbance) and create their own vulnerabilities in the conservation phase, where they typically spend most of their time. In this stage, managers frequently seek to reduce fluctuations in ecological processes and prevent small disturbances in order to increase the efficiency of achieving management goals (e.g., the amount of timber to be harvested; number of houses that can be built; the budget to pay salaries of personnel), increasing the likelihood that even larger disturbances will occur (Holling and Meffe 1996, Walker and Salt 2006). Flood control, for example, reduces flood frequency, which encourages infrastructure development in floodplains where it is vulnerable to the large flood that will eventually occur. Prevention of small insect outbreaks increases the likelihood of larger outbreaks. Management that encourages small-scale disturbances and innovation during the conservation phase reduces the vulnerability to larger disruptions (Holling et al. 1998, Carpenter and Gunderson 2001, Holling et al. 2002a). The specific mechanisms that link stability in the conservation phase to triggers for disruption are described in later chapters.

Release and crisis provide important opportunities for change (Gunderson and Holling 2002, Berkes et al. 2003; Fig. 1.5b). Some of these changes may be undesirable (invasion of an exotic species, dramatic shift in political regimes that decrease social equity), whereas others may be desirable (implementation of innovative policies that are more responsive to change). Recognition of these changing properties of a system through the lens of an adaptive cycle suggests that effective long-term management and policy-making must be highly flexible and adaptive, looking for windows of opportunity for constructive policy shifts.

Most social–ecological systems are spatially heterogeneous and consist of mosaics of subsystems that are at different stages of their adaptive cycles. Interactions and feedbacks among these adaptive cycles operating at different temporal and spatial scales account for the overall dynamics of the system (termed **panarchy**; Fig. 1.6b; Holling et al. 2002b). A forest, for example, may consist of different-aged stands at different stages of regeneration from logging or wildfire. In this case, the system as a whole may be at steady state (a **steady-state mosaic**) even though individual stands are at different stages in their cycles (Turner et al. 2001). In general, there are different benefits to be gained at different phases of the cycle, so policies that permit or foster certain disturbances may be appropriate. Many families contain individuals at various stages of birth, maturation, and death and benefit from the resulting diversity of skills, perspectives, and opportunities. Similarly, in a healthy economy new firms may establish at the same time that other less-efficient firms go out of business. Maintenance of natural cycles of fire or insect outbreak produces wildlife habitat in the early growth phase and prevents excessive fuel accumulation that might otherwise trigger more catastrophic fires. Perhaps the most dangerous management strategy would be to prevent disturbance uniformly throughout a region until all subunits reach a similar state of maturity, making it more likely that the entire system will change synchronously.

Sustainability in a Directionally Changing World

Conceptual Framework for Sustainability Science

A systems perspective provides a logical framework for managing changes in social–ecological systems. To summarize briefly the previous sections, the dynamic interactions of ecological and social processes that characterize most of today's urgent problems necessitate a social–ecological framework for planning and stewardship. Any sustainable solution to a resource issue must be compatible with current social and ecological conditions and their likely future changes. A resource policy that is not ecologically, economically, and culturally sustainable is unlikely to be successful. Sustainable resource stewardship must therefore be multifaceted, recognizing the interactions among ecological, economic, and cultural variables and the important roles that past history and future events play in determining outcomes in specific situations. In addition, systems undergo cyclic changes in their sensitivity to external perturbations, so management solutions that may have been successful at one time and place may or may not work under other circumstances.

The complexity of these dynamics helps frame the types of stewardship approaches that are most likely to be successful. It is unlikely that a rigid set of rules will lead to successful stewardship because key decisions must frequently be made under conditions of novelty and uncertainty. Moreover, under current rapid rates of global environmental and social changes, the current environment for decision-making is increasingly different from past conditions that may be familiar to managers or the future conditions that must be accommodated. The more rapidly the world changes, the less likely that rigid management approaches will be successful. By considering the system properties presented above, however, we can develop resilience-based approaches that substantially reduce the risk of undesirable social–ecological outcomes and increase the likelihood of making good use of unforeseen opportunities. This requires managing for general system properties rather than for narrowly defined production goals. In this section, we present a framework for this approach that is described in detail in subsequent chapters.

Sustaining the desirable features of our current world for future generations is an important societal goal. The challenge of doing so in the face of persistent directional trends in underlying controls has led to an emerging science of sustainability (Clark and Dickson 2003). Sustainability has been adopted as a central goal of many local, national, and international planning efforts, but it is often unclear exactly what it is or how to achieve it. In this book we use the United Nations Environment Programme (UNEP) definition of **sustainability:** the use of the environment and resources to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). According to this definition, sustainability requires that people be able to meet their own needs, i.e., to sustain human **well-being** (that is, the basic material needs for a good life, freedom and choice, good social relations, and personal security) now and in the future (Dasgupta 2001; see Chapter 3). Since sustainability and well-being are value-based concepts, there are often conflicting visions about what should be sustained and how sustainability should be achieved. Thus the assessment of sustainability is as much a political as a scientific process and requires careful attention to whose visions of sustainability are being addressed (Shindler and Cramer 1999). Nonetheless, any vision of sustainability ultimately depends on the life-support capacity of the environment and the generation of ecosystem services (see Chapter 2).

Types and Substitutability of Capital

Sustainability requires that the productive base required to support well-being be maintained or increased over time. **Well-being** can be defined in economic terms as the present value of future **utility**, i.e., the capacity of individuals or society to meet their own needs (Dasgupta and Mäler 2000, Dasgupta 2001). Well-being also has important social and cultural dimensions (see Chapter 3), but the economic definition enables us to frame sustainability in a systems context. Sustainability requires that the total **capital**, or productive base (assets) of the system, be sustained. This capital has natural, built (manufactured), human, and social components (Arrow et al. 2004). **Natural capital** consists of both nonrenewable resources (e.g., oil reserves) and renewable ecosystem resources (e.g., plants, animals, and water) that support the production of goods and services on which society depends. **Built capital** consists of the physical means of production beyond that which occurs in nature (e.g., tools, clothing, shelter, dams, and factories). **Human capital** is the capacity of people to accomplish their goals; it can be increased through various forms of learning. Together, these forms of capital constitute the **inclusive wealth** of the system, i.e., the productive base (assets) available to society. Although not included in the formal definition of inclusive wealth, **social capital** is another key societal asset. It is the capacity of groups of people to act collectively to solve problems (Coleman 1990). Components of each of these forms of capital change over time. Natural capital, for example, can increase through improved management of ecosystems, including restoration or renewal of degraded ecosystems or establishment of networks of marine-protected areas; built capital through investment in bridges or schools; human capital through education and training; and social capital through development of new partnerships to solve problems. Increases in this productive base constitute **genuine investment**. **Investment** is the increase in the quantity of an asset times its value. Sustainability requires that genuine investment be positive, i.e., that the productive base (genuine wealth) not decline over time (Arrow et al. 2004). This provides an objective criterion for assessing whether management is sustainable.

To some extent, different forms of capital can **substitute** for one another, for example, natural wetlands can serve water purification functions that might otherwise require the construction of expensive water treatment facilities. Well-informed leadership may be able to implement more cost-effective solutions to a given problem (a substitution of human for economic capital). However, there are limits to the extent to which different forms of capital can be substituted (Folke et al. 1994). Water and food, for example, are **essential** for survival, and no other forms of capital can completely substitute for them (see Chapter 12). They therefore have extremely high value to society when they become scarce. Declines in the trust that society has in its leadership; sense of cultural identity; the capacity of agricultural soils to retain sufficient water to support production; or the presence of species that pollinate critical crops, for example, cannot be readily compensated by substituting other forms of capital. Losses of many forms of human, social, and natural capital are especially problematic because of the impossibility or extremely high costs of providing appropriate substitutes (Folke et al. 1994, Daily 1997). We therefore focus particular attention on ways to sustain these components of capital, without which future generations cannot meet their needs (Arrow et al. 2004).

Well-informed managers often have guidelines for sustainably managing the components of inclusive wealth. For example, harvesting rates of renewable natural resources should not exceed regeneration rates; waste emissions should not exceed the assimilative capacity of the environment; nonrenewable resources should not be exploited at a rate that exceeds the creation of renewable substitutes; education and training should provide opportunities for disadvantaged segments of society (Barbier 1987, Costanza and Daly 1992, Folke et al. 1994).

The concept of maintaining positive genuine investment as a basis for sustainability is important because it recognizes that the capital assets of social–ecological systems inevitably change over time and that people differ through time and across space in the value that they place on different forms of capital. If the productive base of a system is sustained, future generations can make their own choices about how best to meet their needs. This defines criteria for deciding whether certain practices are sustainable in a changing world. There are substantial challenges in measuring changes in various forms of capital, in terms of both their quantity and their value to society (see Chapter 3). Nonetheless, the best current estimates suggest that manufactured and human capital have increased in the last 50 years in most countries but that natural capital has declined as a result of depletion of renewable and nonrenewable resources and through pollution and loss of the functional benefits of biodiversity (Arrow et al. 2004). In some countries, especially some of the poorer developing nations, the loss of natural capital is larger than increases in manufactured and human capital, indicating a clearly unsustainable pathway of development (MEA 2005d). Some argue that there have also been substantial decreases in social capital as a result of modernization and urban life (Putnam 2000).

Managing Change in Ways that Foster Sustainability

Managing for sustainability requires attention to changes typical of complex adaptive systems. In the previous section we defined criteria to assess sustainability. These criteria are of little use if the system to which they are applied changes radically. Now we must place sustainability in the context of the directional changes in factors that govern the properties of most social–ecological systems. Three broad categories of outcome are possible: (1) persistence of the fundamental properties of the current system through adaptation, (2) **transformation** of the system to a fundamentally different, potentially more desirable state, or (3) passive changes (often degradation to a less-favorable state) of the system as a result of failure of the system to adapt or transform. Intermediate outcomes are also possible, if some components (e.g., ecological subsystems, institutions, or social units) of the system persist, others transform, and others degrade (Turner et al. 2003). Sustainability implies the persistence of the fundamental properties of the system or of active transformation through deliberate substitution of different forms of capital to meet society's needs in new ways. In contrast, degradation implies the loss of inclusive wealth and therefore the potential to achieve sustainability.

How can we manage the dynamics of change to improve the chances for persistence or transformation? Four general approaches have been identified as ways to foster sustainability under conditions of directional change: (1) reduced vulnerability, (2) enhanced adaptive capacity, (3) increased resilience, and (4) enhanced transformability. Each of these approaches emphasizes a different set of processes by which sustainability is fostered (Table 1.2, Fig. 1.7). Vulnerability addresses the nature of stresses that cause change, the sensitivity of the system to these changes, and the adaptive capacity to adjust to change. Adaptive capacity addresses the capacity of actors or groups of actors to adjust so as to minimize the negative impacts of changes. Resilience

TABLE 1.2. Assumptions of frameworks addressing long-term human well-being. Modified from Chapin et al. (2006a).

Framework	Assumed change in exogenous controls	Nature of mechanisms emphasized	Other approaches often incorporated
Vulnerability	Known	System exposure and sensitivity to drivers; equity	Adaptive capacity, resilience
Adaptive capacity	Known or unknown	Learning and innovation	None
Resilience	Known or unknown	Within-system feedbacks and adaptive governance	Adaptive capacity, transformability
Transformability	Directional	Learn from crisis	Adaptive capacity, resilience

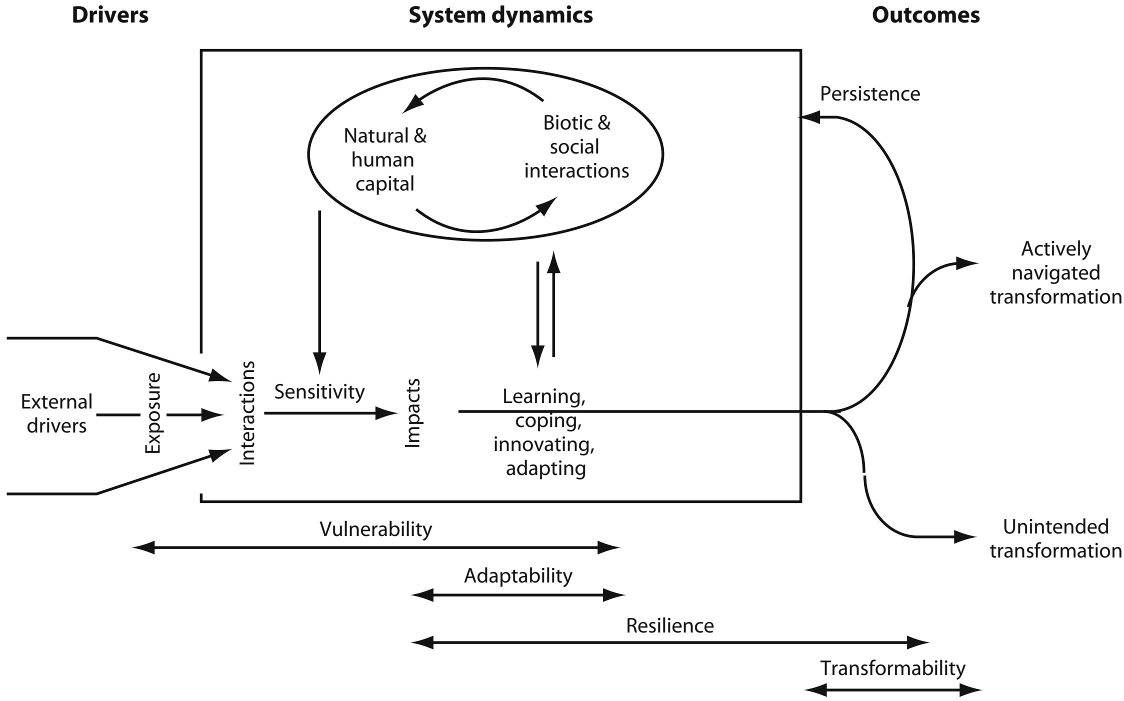


FIGURE 1.7. Conceptual framework linking human adaptive capacity, vulnerability, resilience, and transformability. See text for definition of terms. The system (e.g., household, community, nation, etc.) responds to a suite of interacting drivers (stresses, events, shocks) to produce one of three potential outcomes: (1) persistence of the existing system through resilience; (2) actively navigated transformation to a new, potentially more beneficial state through transformability; or (3) unintended transformation to a new state (often degraded) due to vulnerability and the failure to adapt or transform. These three outcomes are not mutually exclusive, because some components (e.g., ecological subsystems, institutions, or social units) of the system may persist, others transform, and others degrade. The sensitivity of the system to perturbations depends on its exposure (intensity, frequency, and duration) to each perturbation, the interactions among distinct perturbations, and critical properties of the system. The system response to the resulting impacts depends on its adaptive capacity (i.e., its capacity to learn, cope, innovate, and adapt). Adaptive capacity, in turn, depends on the amount and diversity of social, economic, physical, and natural capital and on the social networks, institutions, and entitlements that influence how this capital is distributed and used. System response also depends on effectiveness of cross-scale linkages to changes occurring at other temporal and spatial scales. Those components of the system characterized by strong stabilizing feedbacks and adaptive capacity are likely to be resilient and persist. Alternatively, if the existing conditions are viewed as untenable, a high adaptive capacity can contribute to actively navigated transformation, the capacity to change to a new, potentially more beneficial state of the system or subsystem. If adaptive capacity of some components is insufficient to cope with the impacts of stresses, they are vulnerable to unintended transformation to a new state that often reflects degradation in conditions.

incorporates adaptive capacity but also entails additional system-level attributes of social–ecological systems that provide flexibility to adjust to change. Transformability addresses active steps that might be taken to change the system to a different, potentially more desirable state. Although anthropologists, ecologists, and geographers developed these approaches somewhat independently (Janssen et al. 2006), they are becoming increasingly integrated (Berkes et al. 2003, Turner et al. 2003, Young et al. 2006). This integration of ideas provides policy makers and managers with an increasingly sophisticated and flexible tool kit to address the challenges of sustainability in a directionally changing world. We apply the term **resilience-based ecosystem stewardship** to this entire suite of approaches to sustainability, because of its emphasis on sustaining functional properties of social–ecological systems over the long term despite perturbation and change. These issues represent the core challenges of managing social–ecological systems sustainably. We now briefly outline this suite of approaches.

Vulnerability

Vulnerability is the degree to which a system is likely to experience harm due to exposure to a specified hazard or stress (Turner et al. 2003, Adger 2006). Vulnerability theory is rooted in socioeconomic studies of impacts of events (e.g., floods or wars) or stresses (e.g., chronic food insecurity) on social systems but has been broadened to address responses of entire social–ecological systems. Vulnerability analysis deliberately addresses human values such as equity and well-being. Vulnerability to a given stress can be reduced by (1) reducing exposure to the stress (**mitigation**); (2) reducing sensitivity of the system to stress by sustaining natural capital and the components of well-being, especially for the disadvantaged; and/or (3) increasing adaptive capacity and resilience (see below) to cope with stress (Table 1.3; Turner et al. 2003). The incorporation of adaptive capacity and resilience as integral components of the vulnerability framework (Turner et al. 2003, Ford and Smit 2004) illustrates the integration of different approaches to sustainability science.

TABLE 1.3. Principal sustainability approaches and mechanisms. Adapted from Levin (1999), Folke et al. (2003), Turner et al. (2003), Chapin et al. (2006a), Walker et al. (2006).

Vulnerability
Reduce exposure to hazards or stresses
Reduce sensitivity to stresses
Sustain natural capital
Maintain components of well-being
Pay particular attention to vulnerability of the disadvantaged
Enhance adaptive capacity and resilience (see below)
Adaptive capacity
Foster biological, economic, and cultural diversity
Foster social learning
Experiment and innovate to test understanding
Select, communicate, and implement appropriate solutions.
Resilience
Enhance adaptive capacity (see above)
Sustain legacies that provide seeds for renewal
Foster a balance between stabilizing feedbacks and creative renewal
Adapt governance to changing conditions
Transformability
Enhance diversity, adaptation, and resilience
Identify potential future options and pathways to get there
Enhance capacity to learn from crisis
Create and navigate thresholds for transformation

Exposure to a stress can be reduced by minimizing its intensity, frequency, duration, or extent. Prevention of pollution or banning of toxic pesticides, for example, reduces the vulnerability of people who would otherwise be exposed to these hazards. Mitigation (reduced exposure) is especially challenging when the stress is the cumulative effect of processes occurring at scales that are larger than the system being managed. Anthropogenic contributions to climate warming through the burning of fossil fuels, for example, is globally dispersed, so it cannot be reversed by actions taken solely by those regions that experience greatest impacts of climatic change (McCarthy et al. 2005). Other globally or regionally dispersed stresses include inadequate supplies of clean water and uncertain availability of nutritious food (Steffen et al. 2004, Kasperson et al. 2005).

Sensitivity to a stress can be reduced in at least three ways: (1) sustaining the slow ecological variables that determine natural capital; (2) maintaining key components of well-being; and (3) paying particular attention to the needs of the disadvantaged segments of society, who are generally most vulnerable. The poor or disadvantaged, for example, are especially vulnerable to food shortages or economic downturns, and people living in floodplains or the wildland–urban interface are especially vulnerable to flooding or wildfire, respectively. An understanding of the causes of differential vulnerability can lead to strategies for targeted interventions to reduce overall vulnerability of the social–ecological system.

The causes of differential vulnerability are often deeply rooted in the slow variables that govern the internal dynamics of society, such as power relationships or distribution of land-use rights among segments of society (see Chapter 3). Conventional vulnerability analysis assumes that the stresses are known or predictable (i.e., either steady state or changing in a predictable fashion). However, long-term reductions in vulnerability often require attention to adaptive capacity and resilience at multiple scales in addition to targeted efforts to reduce exposure and sensitivity to known stresses.

Adaptive Capacity

Adaptive capacity (or adaptability) is the capacity of actors, both individuals and groups, to respond to, create, and shape variability and change in the state of the system (Folke et al. 2003, Walker et al. 2004, Adger et al. 2005). Although the actors in social–ecological systems include all organisms, we focus particularly on people in addressing the role of adaptive capacity in social–ecological change, because human actors base their actions not only on their past experience but also on their capacity to *plan for the future* (**reflexive action**). This contrasts with **evolution**, which shapes the properties of organisms based entirely on their genetic responses to *past* events. Evolution has no forward-looking component. Adaptive capacity depends on (1) biological, economic, and cultural diversity that provides the building blocks for adjusting to change; (2) the capacity of individuals and groups to learn how their system works and how and why it is changing; (3) experimentation and innovation to test that understanding; and (4) capacity to govern effectively by selecting, communicating, and implementing appropriate solutions (Table 1.3) We discuss the social and cultural bases of adaptive capacity in Chapters 3 and 4 and here focus on its relationship to system properties.

Sources of biological, economic, and cultural diversity provide the raw material on which adaptation can act (Elmqvist et al. 2003, Norberg et al. 2008). In this way it defines the options available for adaptation. People can augment this range of options through learning, experimentation, and innovation. This capacity to create new options is strongly influenced by people's access to built, natural, human, and social capital. Societies with little access to capital are constrained in their capacity to adapt. People threatened with starvation, for example, may degrade natural capital by overgrazing to meet their immediate food needs, thereby reducing their potential to cope with drought or future food shortage. Rich countries, on the other hand, have greater capacity to engineer solutions to cope with floods, droughts, and disease outbreaks. Natural capital also contributes in important ways to adaptive capacity, although its role is often unrecognized until it has been degraded. Systems that have experienced severe soil erosion, for example, have fewer options with which to experiment and innovate during times of drought, and highly engineered systems that have lost their capacity to store floodwaters have fewer options to adapt in response to floods. The role of human capital in adaptive capacity is especially important. It is much more than formal education. It depends on an understanding of how the system responds to change, which often comes from experience and local knowledge of past responses to extreme events or stresses. As the world changes, and new hazards and stresses emerge, this understanding may be insufficient. Willingness to innovate and experiment to test what has been learned and to explore new approaches is crucial to adaptive capacity.

Social capital through networking to select, communicate, and implement potential solutions is another key component of adaptive capacity. Leadership, for example, is often critical in building trust, making sense of complex situations, managing conflict, linking actors, initiating partnerships among groups, compiling and generating knowledge, mobilizing broad support for change, and developing and communicating visions for change (Folke et al. 2005; see Chapter 5). It takes more than leaders, however, for society to adapt to change. Social networks are critical in effectively mobilizing resources at times of crisis (e.g., war or floods) and in providing a safety net for vulnerable segments of society (see Chapters 4 and 5).

In the context of sustainability, adaptive capacity represents the capacity of a social–ecological system to make appropriate substitutions among forms of capital to maintain or enhance inclusive wealth. In this way the system retains the potential for future generations to meet their needs.

Resilience

Resilience is the capacity of a social–ecological system to absorb a spectrum of shocks or perturbations and to sustain and develop its fundamental function, structure, identity, and feedbacks through either recovery or reorganization in a new context (Holling 1973, Gunderson and Holling 2002, Walker et al. 2004, Folke 2006). The unique contribution of resilience theory is the recognition and identification of several possible system properties that foster renewal and reorganization after perturbations (Holling 1973). Resilience depends on (1) adaptive capacity (see above); (2) biophysical and social legacies that contribute to diversity and provide proven pathways for rebuilding; (3) the capacity of people to plan for the long term within the context of uncertainty and change; (4) a balance between stabilizing feedbacks that buffer the system against stresses and disturbance and innovation that creates opportunities for change; and (5) the capacity to adjust governance structures to meet changing needs (Holling and Gunderson 2002, Folke et al. 2003, Walker et al. 2006; Table 1.3). Loss of resilience pushes a system closer to its limits. When resilience has been eroded, a disturbance, like a disease, storm, or stock market fluctuation, that previously shook and revitalized the resilient system, might now push the fragile system over a threshold into an alternative state (a **regime shift**) with a new trajectory of change. Such system changes radically alter the flow of ecosystem services (Chapter 2) and associated livelihoods and well-being of people and societies. Clearly, resilience is an essential feature of resource stewardship under conditions of uncertainty and change, so this approach to resource management is even more important today than it has been in the past.

We have already discussed the role of stabilizing feedbacks in buffering systems from change and the role of adaptive capacity in coping with the impacts of those changes that occur. Sources of diversity, which is essential for adaptation, are especially important in the focal system and surrounding landscape at times of crisis, i.e., during the renewal phase of adaptive cycles, when there is less resistance to establishment of new entities. Fostering small-scale variability and change logically contributes to resilience because it maintains within the system those components that are well adapted to each phase of the adaptive cycle—ranging from the renewal to the conservation phase. This reduces the likelihood that the inevitable disturbances will have catastrophic effects. Conversely, preventing small-scale disturbances such as insect outbreaks or fires tends to eliminate disturbance-adapted components, thereby reducing the capacity of the system to cope with disturbance.

Biophysical and social legacies contribute to resilience through their contribution to diversity. Legacies provide species, conditions, and perspectives that may not be widely represented in the current system. A buried seed pool or stems that resprout after fire, for example, give rise to a suite of early successional species that are well adapted to postdisturbance conditions but may be uncommon in the mature forest. Similarly, the stories and memories of elders and the written history of past events often provide insight into ways in which people coped with past crises as well as ideas for future options that might not otherwise be considered. This often occurs by drawing on **social memory**, the social legacies of knowing how to do things under different circumstances. A key challenge is how to foster and maintain social memory at times of gradual change, so it is available when a crisis occurs.

One of the key contributions of resilience theory to resource stewardship is the recognition that complex adaptive systems are constantly changing in ways that cannot be fully predicted or controlled, so decisions must always be made in an environment of uncertainty. Research and awareness of processes occurring at a wide range of scales (e.g., the dynamics of potential pest populations or behavior of global markets) can reduce uncertainty (Adger et al. 2005, Berkes et al. 2005), but managing for flexibility to respond to unanticipated changes is essential. This contrasts with steady-state management approaches that seek to reduce variability and change as a way to facilitate efficient harvest of a given resource such as fish or trees (Table 1.1).

Transformability and Regime Shifts

Transformability is the capacity to reconceptualize and create a fundamentally new system with different characteristics (Walker et al. 2004; see Chapter 5). There will always be a creative tension between resilience (fixing the current system) and transformation (seeking a new, potentially more desirable state) because actors in the system usually disagree about when to fix things and when to cut losses and move to a new alternative structure (Walker et al. 2004). Actively navigated transformations require a paradigm shift that reconceptualizes the nature of the system. During transformation, people recognize (or hypothesize) a fundamentally different set of critical slow variables, internal feedbacks, and societal goals. Unintended transformations can also occur in situations where management efforts have prevented adjustment of the system to changing conditions, resulting in a fundamentally different system (often degraded) characterized by different critical slow variables and feedbacks. The dividing line between persistence of a given system and transformation to a new state is sometimes fuzzy. Total system collapse seldom occurs (Turner and McCandless 2004, Diamond 2005). Nonetheless, actively navigated transformations of important components of a system are frequent (e.g., from an extractive to a tourism-based economy). In general, diversity, adaptive capacity, and other components of resilience enhance transformability because they provide the seeds for a new beginning and the adaptive capacity to take advantage of these seeds.

Transformations are often triggered by crisis, so the capacity to plan for and recognize opportunities associated with crisis contributes to transformability (Gunderson and Holling 2002, Berkes et al. 2003). **Crisis** is a time when society, by definition, agrees that some components of the present system are dysfunctional. During crisis, society is more likely to consider novel alternatives. It is also a time when, if novel solutions are not seized, the system can become entrenched in the very policies that led to crisis, increasing the likelihood of unintended transformations. Climate-induced increases in wildfires in the western USA, for example, threaten homes that have been built in the wildland–urban interface. One potential transformation would be policies that cease assuming public responsibility for private homes built in remote fire-prone areas and instead encouraged more dense development of areas that could be protected from fire and served by public transportation. This would reduce the need and cost of wildfire suppression, increase the economic efficiency of public transportation, and reduce the use of fossil fuels. Alternatively, current policies of fire suppression and dispersed residential development in forested lands might persist and magnify the risk of catastrophic loss of life and property as climate warming increases wildfire risk and fire suppression leads to further fuel accumulation.

Sometimes systems exhibit abrupt transitions (regime shifts) to alternate states because of threshold responses to persistent changes in one or more slow variables. Continued phosphorus inputs to clearwater lakes, for example, may lead to abrupt transitions to a turbid-water algal-dominated regime (Carpenter 2003). Similarly, persistent overgrazing can cause shrub encroachment and transition from grassland to shrubland (Walker et al. 2004). Regime shifts are large changes in ecosystems that include both changes in stability domains of a given system (e.g., clearwater–turbid-water transitions; Fig. 1.7d) and system transformations (Carpenter 2003, Groffman et al. 2006).

Challenges to Sustainability

The major challenges to sustainability vary temporally and regionally. Issues of sustainability are often prominent in developing nations, especially where substantial poverty, inadequate educational opportunities, and insufficient health care limit well-being (Kasperson et al. 2005). These situations sometimes coincide with a high potential for environmental degradation, for example, soil erosion and contamination of water supplies, as people try to meet their immediate survival needs under circumstances of inadequate social and economic infrastructure. **Sustainable development** seeks to improve well-being, while at the same time protecting the natural resources on which society depends (WCED 1987). In other words, it seeks directional changes in some underlying controls, but not others. Questions are often raised about whether sustainable development can indeed be achieved, given its twin goals of actively promoting economic development while sustaining natural capital. The feasibility of sustainable development depends on the multiple effects of development on system properties and the extent to which these new system properties can be sustained over the long term. In other words, how does development influence the slow variables that govern the properties of social–ecological systems and how can they be redirected or transformed for improving the options of well-being without degrading inclusive wealth? Finding sustainable solutions usually requires active engagement of **stakeholders** (groups of people affected by policy decisions) who must live with, and participate in, the implementation of potential solutions.

Enhancing the sustainability of nations with greater wealth is equally challenging. Countries such as the USA, for example, consume fossil fuels at per-capita rates that are fivefold greater than the world average and frequently use renewable resources more rapidly than they can be replenished. Here the challenge is to avoid degradation of the ecological and cultural bases of well-being over the long term so that people in other places and in future generations can meet their own needs (Plate 3).

In summary, virtually all social–ecological systems are undergoing persistent directional changes, as a result of both unplanned changes in climate, economic systems, and culture and deliberate planning to improve well-being. Efforts to promote sustainability must therefore recognize that many of the attributes of social–ecological systems will inevitably change over the long term and seek ways to guide these changes along sustainable pathways.

Roadmap to Subsequent Chapters

The first section of the book presents the general principles needed for sustainable stewardship in a changing world (Table 1.4). Chapter 1 provides a framework for understanding change and the factors that influence sustainability under conditions of change. A clear message from this chapter is that social–ecological systems are complex and require an understanding of the interactions among ecological, economic, political, and cultural processes. Consequently, key resource-management issues cannot be solved by disciplinary experts but require an integrated understanding of many disciplines. Chapter 2 describes the principles of ecosystem management to sustain the delivery of ecosystem services to society. Chapter 3 describes the range of economic, cultural, and political factors that shape well-being and use of ecosystem services. Chapter 4 then describes the institutional dimensions of human interactions with ecosystems. Chapter 5 explores the processes by which social–ecological systems transform to a fundamentally different system with different controls and feedbacks.

The second section of the book applies the general principles developed in the first section to specific types of social–ecological systems and their prominent resource–stewardship challenges (Table 1.4), including conservation (see Chapter 6), forests (see Chapter 7), drylands (see Chapter 8), lakes and rivers

TABLE 1.4. Resource–stewardship challenges and the chapters in which each is emphasized.

Issue	Chapter where emphasized
Social-ecological interactions	All chapters (2–15)
Global change	Concepts (2–5), Global (14), Systems (6–13)
Ecological sustainability	Ecosystems (2), System chapters (6–14)
Ecosystem restoration	Ecosystems (2), Drylands (8)
Biodiversity conservation	Ecosystems (2), Conservation (6), Forests (7)
Invasive species	Ecosystems (2), Freshwaters (9)
Landscape management	Ecosystems (2), Drylands (8), Freshwaters (9)
Range management	Ecosystems (2), Drylands (8)
Wildlife management	Ecosystems (2), Conservation (6), Drylands (8)
Fisheries management	Freshwaters (9), Oceans (10), Coastal (11)
Water management	Ecosystems (2), Drylands (8), Freshwaters (9)
Disturbance management	Ecosystems (2), Forests (7), Freshwaters (9)
Pollution	Ecosystems (2), Agriculture (12), Cities (13)
Urban development	Livelihoods (3), Forests (7), Cities (13)
Sustaining human livelihoods	Livelihoods (3), Conservation (6), Coastal (11)
Social and environmental justice	Livelihoods (3), Coastal (11), Cities (13), Global (14)
Sustainable development	Livelihoods (3), Agriculture (12)
Local and traditional knowledge	Institutions (4), Conservation (6), Drylands (8)
Property rights and the commons	Institutions (4), Oceans (10), Coastal (11)
Natural resource policy	Institutions (4), System chapters (6–14)
Subsistence harvest	Institutions (4), Conservation (6)
Resource co-management	Institutions (4), Conservation (6), Coastal (11)
Adaptive management	Institutions (4), Drylands (8), Oceans (10)
Long-term planning	Transformation (5), Forests (7), Global (14)
Managing thresholds	Transformation (5), Drylands (8), Oceans (10)
Adaptive governance	Transformation (5), Forests (7), Global (14)
Thresholds and regime shifts	Transformation (5), Drylands (8), Freshwaters (9)

(see Chapter 9), oceans and estuaries (see Chapters 10 and 11), food production systems (see Chapter 12), cities and suburbs (see Chapter 13), and the entire Earth (see Chapter 14). Each of these chapters describes the system properties and dynamics that are especially important in that system, key management issues, and potential social–ecological thresholds. Each chapter then describes a few case studies that illustrate resilient or non-resilient management and outcomes and how the unique properties of each system shape human–environment interactions and sustainability constraints and opportunities. Each system chapter emphasizes selected general principles that were described in the first section of the book.

The final chapter (see Chapter 15) summarizes some of the major strategies that have proven valuable for managing social–ecological systems and the lessons learned from previous chapters about the role of resilience and adaptation in sustainable stewardship.

Review Questions

1. What is resilience-based resource stewardship? How does it differ from steady-state resource management, and why are these differences important in the current world?
2. How do different types of feedbacks influence the stability and resilience of a system?
3. What are the *mechanisms* by which complex adaptive systems respond to changes? Do they always respond in the same way to a given perturbation? Why or why not? In social–ecological systems, why does a given policy sometimes have different effects when implemented at different times or places?

4. Why does the sensitivity of social–ecological systems to perturbations depend on the time since the previous perturbation? What are the advantages and disadvantages of managing systems to prevent disturbances from occurring?
5. What are the processes by which vulnerability, adaptive capacity, resilience, and transformability influence sustainability?

Additional Readings

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