

**Human activities influence all of Earth's ecosystems. This chapter summarizes the principles by which important ecological properties can be sustained to meet the needs of ecosystems and society.**

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## Introduction

**Growth of the human population and our use of resources have altered ecosystems more rapidly and extensively in the last 50 years than in any comparable period of human history** (Fig. 15.1; MEA 2005). Accelerating human impacts are causing global changes in most major ecosystem controls: climate (global climate change), soil and water resources (nitrogen deposition, erosion, diversions), disturbance regime (land-use change, fire control), and functional types of organisms (species introductions and extinctions). All ecosystems are therefore experiencing directional changes in ecosystem controls, creating novel conditions and, in many cases, amplifying (positive) feedbacks that accelerate changes to new types of ecosystems. These changes in interactive controls inevitably alter the properties of ecosystems, often to the detriment of society.

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## A Focal Issue

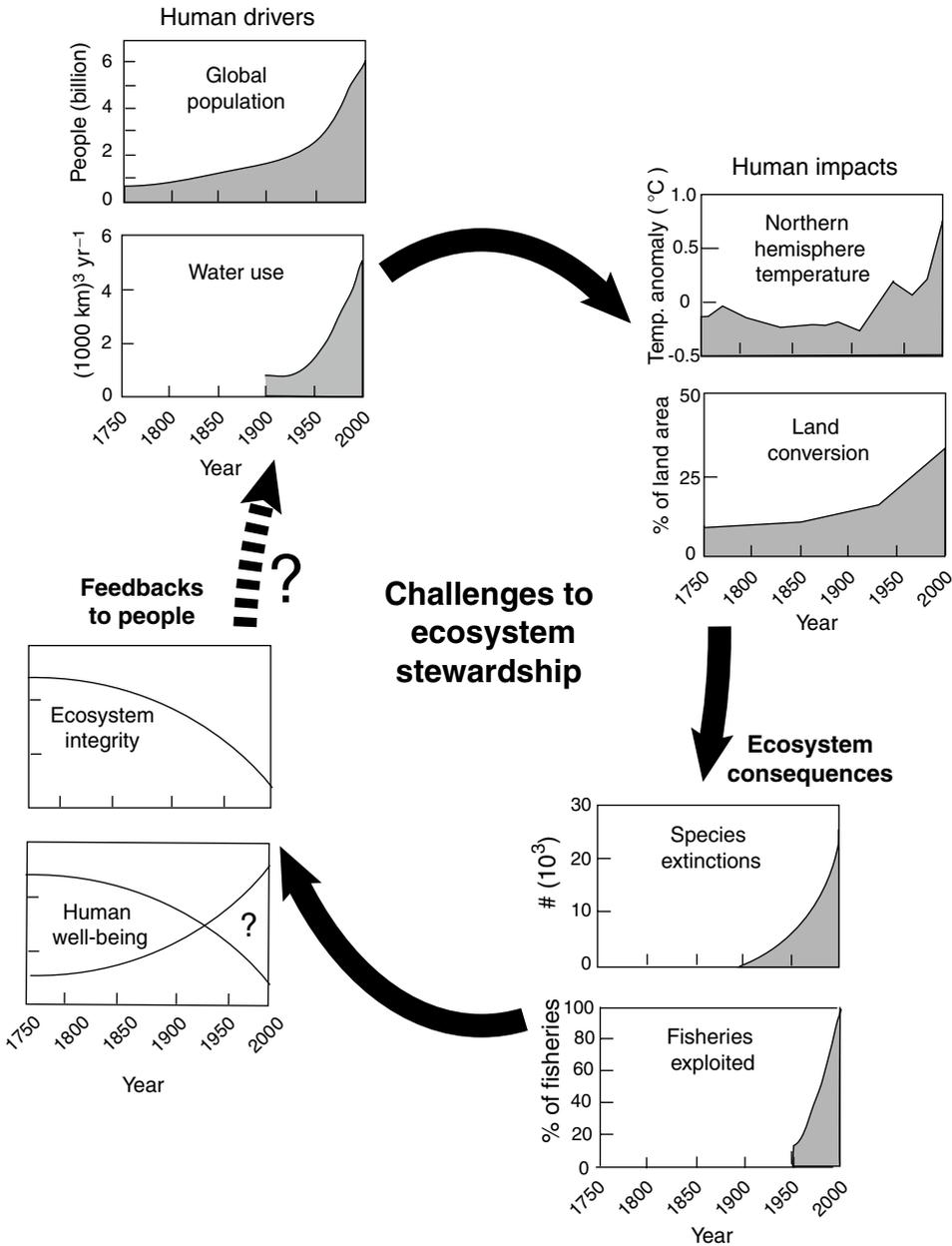
**Given that human activities have and will continue to shape ecosystems of the planet, how can these be managed to sustain ecosystem**

**properties and the services they provide to society** (Fig. 15.2)? In this chapter, we describe some general principles that contribute to sound ecosystem management. Maintaining Earth's ecosystems, even the "wild" ones, in the face of anthropogenic changes requires new management approaches that recognize the increasing human domination of the biosphere (Palmer et al. 2004). We review management approaches that draw on ecosystem ecology and other sciences to manage and sustain ecosystems and the benefits we derive from them.

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## Sustaining Social–Ecological Systems

**People and nature are interconnected components of coupled social–ecological systems.** People inhabit 80% of the ice-free land surface of the planet and therefore are integral components of most ecological systems (Ellis and Ramankutty 2008). Many of the negative human impacts on ecosystems are unintended, as people seek to meet multiple desires and needs within a social context. Failure to recognize key linkages between ecosystems and society creates vulnerabilities that could be avoided by proper **ecosystem management**, i.e., resource management that promotes long-term sustainability of ecosystems and the delivery of essential ecosystem goods and services to society. The loss of flood control associated with wetland drainage and reduced sediment delivery to



**Fig. 15.1** Challenges to ecosystem management and 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 well-being, which feed back to further changes in human drivers. Redrawn from Chapin et al. (2009) with panels from Steffen et al. (2004)

barrier islands during urban development of New Orleans, for example, was overlooked until Hurricane Katrina caused major flooding and loss of life and property in 2005 (Box 15.1; Kates et al. 2006). Ecosystem managers must

therefore be aware not only of environmental and biological factors that influence ecosystems but also of the social and political forces that influence decisions that cause unintended effects on ecosystems (Fig. 15.3).



**Fig. 15.2** Human actions are modifying ecosystems at scales that influence the Earth System. Society now faces the challenge of managing its relationship to the biosphere

to sustain and enhance the benefits provided by ecosystems to support human well-being. Photograph from istockphoto

#### **Box 15.1 Social-Ecological Interactions and the Flooding of New Orleans**

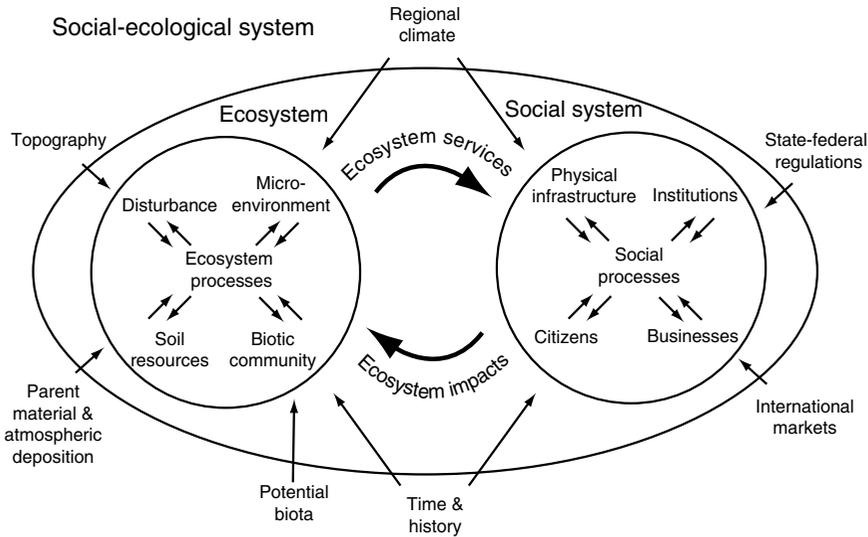
The southeastern coastal plain of the U.S. is low and flat, with much of the land created out of sediments delivered to the coast by major rivers. Louisiana's offshore barrier islands and extensive wetlands that protect cities from storms and floods are products of this fluvial-delta system (NRC 2006). The construction of levees and reservoirs has reduced sediment delivery that maintains these natural protective features. Land subsidence resulting from the extraction of oil and gas, drainage of low-lying

areas, and other development activities also contributes to vulnerability to storms and flooding (NRC 2006). New Orleans, for example, has subsided an average of  $5 \text{ mm year}^{-1}$ , so much of New Orleans is below sea level and persists only because of a system of levees and pumps. Storm surges caused by Hurricane Katrina broke through the system of protective levees surrounding New Orleans in 2005, causing extensive loss of life and property (Kates et al. 2006).

## **Sustainability**

**Sustainability requires recognition of tradeoffs resulting from choices that influence social–ecological systems today and in the future.** Most decisions that negatively affect ecosystems

are not malicious but reflect choices to pursue certain socioeconomic benefits. Mining and overgrazing, for example, generally occur through efforts to meet people's desires for minerals and food, respectively. The ecological consequences of these actions are sometimes less obvious or of



**Fig. 15.3** Controls over the functioning of social–ecological systems. Human impacts on ecosystems are mediated by a variety of social processes, and society benefits from the services provided by ecosystems. Modified from Whiteman et al. (2004)

less immediate concern to the decision maker than are short-term social or economic benefits. Ecologists can play an important role in these decisions by documenting potential **tradeoffs** that influence ecological and social risks and opportunities (Matson 2009). Sustainability provides an important framework for clarifying the consequences of choices facing society. These choices are particularly stark for developing nations, where people depend very directly on ecosystems for survival but also seek to escape conditions of persistent poverty and poor quality of life. In 1987, the Brundtland Commission (WCED 1987) proposed to the United Nations a sustainability framework that addressed this twin challenge of meeting needs for ecological conservation and human development. **Sustainability**, as defined in that report, is the use of the environment and resources to meet the needs of the present without compromising the ability of future generations to meet their needs. Sustainability does not require that ecosystems remain unchanged, which would be impossible in a rapidly changing world. Moreover, we cannot know with certainty what future generations will want. Sustainability simply requires that the productive base available to future generations be sustained

in ways that provide them with the opportunities to make their own choices.

The productive base on which society depends has both ecological and socioeconomic dimensions. 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 (Daily 1997). **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 (Dasgupta 2001, Chapin et al. 2009). 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 (inclusive 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 cost-effective solutions to a given problem (a substitution of human capital for economic capital). There are, however, limits to the extent to which different forms of capital can be substituted. Water and food, for example, are **essential** for survival, and no other forms of capital can completely substitute for them. They therefore have extremely high value to society when they become scarce. Similarly, other forms of capital cannot readily compensate for declines in the capacity of agricultural soils to retain enough water for crop production, the presence of species that pollinate critical crops, a sense of cultural identity, or the trust that society has in its leadership. 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 critical components of capital, without which future generations cannot meet their needs (Arrow et al. 2004).

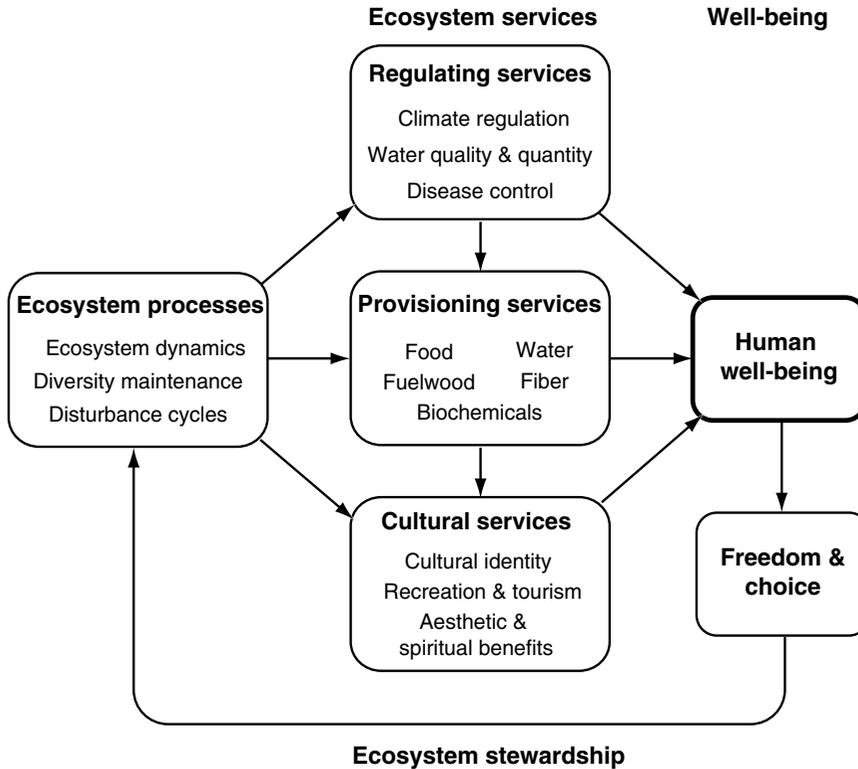
Well-informed managers often have guidelines for sustainably managing the components

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 to improve their quality of life (Barbier 1987, Costanza and Daly 1992, Folke et al. 1994). These guidelines provide a framework for many of the practical decisions faced by ecosystem managers.

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 value to society. 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; MEA 2005). In some of the poorer developing nations, the loss of natural capital has been larger than increases in manufactured and human capital, indicating a clearly unsustainable pathway of development (MEA 2005).

## **Ecological Dimensions of Sustainability**

**Ecosystem services provide a pragmatic framework for managing ecological sustainability.** Although natural capital is a fundamental



**Fig. 15.4** Linkages among ecosystem processes, ecosystem services, and the well-being of society, a framework developed by the Millennium Ecosystem Assessment (MEA 2005). Ecosystem processes are the foundation for ecosystem services that are directly used by society and

which strongly influence human well-being. Human actions influence the life-support system of the planet through effects on environment (e.g., climate) and on ecosystems. Redrawn from Chapin (2009)

measure of the capacity of ecosystems to meet society's needs over the long term, it provides little guidance to ecosystem managers seeking to address specific social–ecological issues such as multiple-use forestry or ocean management. Different ecosystem configurations may reflect similar levels of natural capital but provide different patterns of **ecosystem services**, the benefits that society derives from ecosystems. Ecosystems provide well-recognized **provisioning services (goods)**, including water, timber, forage, fuels, medicines, and precursors to industrial products that are harvested from ecosystems. Ecosystems also provide **regulatory services** such as recycling of water and chemicals, mitigation of floods, pollination of crops, and cleansing of the atmosphere, as well as **cultural services** that meet recreational, aesthetic, and spiritual needs (Fig. 15.4; Table 15.1; Daily 1997, MEA

2005). All of these services depend on ecosystem processes, sometimes known as supporting services. These processes include biogeochemical cycles, diversity maintenance, and disturbance cycles. Unless these underlying ecosystem properties are maintained, other services that are more directly recognized and valued by society cannot be sustained.

The overuse or misuse of resources can alter the functioning of ecosystems and the services they provide. Land-use change, for example, can degrade the capacity of watersheds to purify water, leading to large water-treatment costs to cities (Grove 2009). Degradation and loss of wetlands can expose communities to increased damage from floods and storm surges (Kates et al. 2006). Decimation of populations of insect pollinators has reduced yields of many crops (Ricketts et al. 2004). Introductions and invasions of non-native

**Table 15.1** General categories of ecosystem services and examples of the societal benefits that are most directly affected. Modified from Chapin (2009)

Ecosystem services	Direct benefits to society
Ecosystem processes (supporting services)	
Maintenance of soil resources	Nutrition, shelter
Water cycling	Health, waste management
Carbon and nutrient cycling	Nutrition, shelter
Maintenance of disturbance regime	Safety, nutrition, health
Maintenance of biological diversity	Nutrition, health, cultural integrity
Provisioning services	
Fresh water	Health, waste management
Food and fiber	Nutrition, shelter
Fuelwood	Warmth, health
Biochemicals	Health
Genetic resources	Nutrition, health, cultural integrity
Regulating services	
Climate regulation	Safety, nutrition, health
Erosion, water quantity/quality, pollution	Health, waste management
Disturbance propagation	Safety
Control of pests, invasions, and diseases	Health
Pollination	Nutrition
Cultural services	
Cultural identity and cultural heritage	Cultural integrity, values
Spiritual, inspirational, and aesthetic benefits	Values
Recreation and ecotourism	Health, values

species such as killer bees, fire ants, and zebra mussels, through the actions of humans, cause enormous damage to living resources and threaten human health (Patz et al. 2005, Díaz et al. 2006). Human activities also indirectly affect ecosystem goods and services through changes in the atmosphere, hydrologic systems, and climate (see Chap. 14).

Management decisions often involve choices that reflect tradeoffs among ecosystem services. Forest harvest, for example, yields forest products at the expense of recreational opportunities provided by the uncut forest. Policies that enhance recreational values to snow machine users may diminish their value to cross-country skiers. Deforestation of tropical forests may provide local users with both forest products and land to support agriculture but degrade soils in ways that diminish the livelihood opportunities for future generations. An important step in ecosystem management is to assess potential impacts of decisions on *multiple* ecosystem services. This is challenging, given the huge number of services

provided by ecosystems and uncertainties in their responses to a particular action (Table 15.1; Box 15.2). It is often pragmatic to focus particularly on a few **critical ecosystem services**, those services that are most vulnerable to change, have fewest options for technological or ecological substitution, and are most valued by society (A. Kinzig, personal communication).

Scenarios of likely outcomes enable managers and other **stakeholders** (people who are affected by outcomes) to compare the effects on ecosystem services of alternative policy options (Peterson et al. 2003, Carpenter et al. 2006). Zoning decisions about development options on lakeshore property, for example, influence not only the type of development that is likely to occur, but also pollutant levels, fish stocks, and the recreational opportunities of current and future users.

Once critical ecosystem services are identified and their likely responses to particular actions are estimated, people are still faced with difficult choices between alternative uses of the environment. Should a wetland be preserved for its cultural

**Box 15.2 Assessing Tradeoffs Among Ecosystem Services: Hydropower Versus Conservation in New Zealand**

Most policy choices that influence ecosystems involve tradeoffs among different balances of ecosystem services. The political controversy that developed over policies related to the balance between hydropower development and conservation in Fiordland, New Zealand illustrate the role that ecosystem management can play in assessing tradeoffs and negotiating favorable social–ecological outcomes (Mark et al. 2001). The New Zealand Government agreed in 1963 to build a hydropower facility to provide the electricity to a multi-national aluminum smelter that the government considered important to diversifying the national economy, providing local employment, and reversing a population drift within New Zealand. This involved diverting New Zealand's second-largest river (Waiiau River) through a tunnel via a hydroelectric station into a pristine marine sound in Fiordland. In order to maximize power generation, the government planned a second phase that would raise by up to 24 m the levels of one of the two major lakes that are the main gateway to Fiordland National Park, New Zealand's largest national park and a World Heritage Site.

Public concern over the ecological and aesthetic implications of raising the lake levels to meet the power demand of the smelter eventually led to ecological studies that documented the consequences of greatly exceeding the maximum historical lake levels (tree mortality) or minimum lake level (lake shore slumping). These findings of substantial and highly detrimental ecological consequences of lake-level manipulation led to a petition signed by about 10% of the nation's population demanding that the hydroelectric contract with the smelter be renegotiated to avoid lake raising and to minimize environmental impacts. The debate over this issue led to a change in central government and establishment of a group of Lake

Guardians to recommend ecological and engineering guidelines to minimize environmental impacts and meet industry's power needs within the normal range of lake-level variation. In the context of these findings, new legislation stipulated that this hydroelectric project must manage the water level sustainably. Under this legislation, the government then assembled about 20 stakeholder groups to oversee renegotiation of the resource management of water-related ecosystem services. After 5 years of negotiation and collection of additional information, consensus was reached about water management to maximize ecological integrity and provide acceptable levels of electricity to the smelter. These included maintaining lake levels within their natural historic limits, guaranteed minimum flow of the Waiiau River to restore habitat for fish and other biota, restoration of wetlands that had been modified by previous river management, compensation to local indigenous (Maori) peoples for loss of traditional food resources, and maximizing power production within these constraints. The final negotiated agreement sustained most of the ecosystem services that had been discussed and was not contested by any of the 20 stakeholder groups.

This case study illustrates several general issues about ecosystem tradeoffs: (1) Assessing both the ecological and socioeconomic consequences of important policy changes is essential. Decisions that ignore either the ecological or socioeconomic consequences are likely to be unsustainable. (2) Big issues are not easy to resolve and often require enough discussion to develop trust and understanding among user groups. (3) Enduring solutions benefit from long-term environmental monitoring, as well as input and negotiation among multiple users committed to achieving a compromise that is mutually acceptable.

and aesthetic assets, used for sewage treatment, or drained and converted to agriculture? Which services should freshwater systems be managed for? Individuals and societies are constantly making decisions about how to use ecosystem goods and services. These decisions, however, often emphasize short-term economic benefits and assume that ecosystem services that might be lost are “free” and therefore have zero cost if they are degraded (Daily et al. 2000).

**Valuation of ecosystem services** is one way to organize information to help inform such decisions (Daily et al. 2000). Valuation of ecosystem services requires sound ecological information and a clear understanding of alternatives and impacts. Ecological understanding is critical, for example, to characterize the services provided by ecosystems and the processes by which they are generated. This information is often site specific, so local and traditional ecological knowledge is needed. Ecological and economic information must then be integrated to make sound decisions.

In some cases, the economic worth of ecosystem services can be estimated directly from market values of lands or products or from costs that are avoided by retaining the service (e.g., avoided cost of water treatment by retaining wetlands). In other cases, surveys or other indirect approaches are required that assess the values that people place on alternative outcomes (Goulder and Kennedy 1997). Once estimated, the economic values of ecosystem services (or costs of their degradation) can be considered explicitly in decisions that influence sustainability. The protection of highly valued and well-understood services (such as clean water) through the protection of ecosystems is increasingly viewed as a wise alternative to expensive construction and engineering projects (Box 15.3). With increasing knowledge, the benefits of protecting the less-known ecosystem services will become more widely recognized.

We address human dimensions of sustainability later in the context of managing social–ecological systems.

### **Box 15.3 Water Purification for New York City**

New York City has a long tradition of clean water. This water, which originates in the Catskill Mountains, was once bottled and sold because of its high purity. In recent years, the Catskills natural ecological purification system has been overwhelmed by sewage and agricultural runoff, causing water quality to drop below accepted health standards. The cost of a filtration plant to purify this water was estimated at \$6–\$8 billion in capital costs, plus annual operating costs of \$300 million, a high price to pay for what once could be obtained for free (NRC 2000, Pires 2004).

This high cost prompted investigation of the cost of restoring the integrity of the watershed’s natural purification services. The cost of this environmental solution was approximately \$1 billion to purchase and halt development on critical lands within the watershed, to compensate landowners for restrictions on private development, and to subsidize the improvement of septic systems. The huge cost savings provided by ecosystem services was selected by the city as the preferred alternative. This choice provided additional valuable services including flood control and sequestration of carbon in plants and soils.

## Conceptual Framework for Ecosystem Management

**Ecosystem management seeks to sustain or enhance the functional properties of ecosystems that support biodiversity and the ecosystem services on which society depends.** Given the continual changes (and often directional trends) in the interactive controls that regulate ecosystem processes, it is more practical to manage ecosystems for sustainability of *general properties* such as productive potential and resilience to change than to attempt to prevent all fluctuations and changes. Soil resources, biodiversity, and disturbance regimes are interactive controls that are often affected by human activities and have particularly strong effects on ecosystems and the services they provide (see Chap. 1).

## Sustaining Soil Resources

**Soils and sediments are key slow variables that regulate ecosystem processes by providing resources required by organisms.** The controls over the formation, degradation, and resource-supplying potential of soils and sediments are therefore central to sound ecosystem management and to sustaining the natural capital on which society depends (see Chap. 3). The quantity of soil in an ecosystem depends largely on the balance between inputs from weathering or deposition and losses from erosion. In addition, organisms, especially plants, add organic matter to soils through death of tissues and individuals, which is offset by losses through decomposition. In general, the presence of a plant canopy and litter layer minimizes erosion by reducing the impact of raindrops on the surface soil and the resulting decline in water infiltration. Human activities that reduce vegetation cover can increase erosion rates by several orders of magnitude, causing soils that may have accumulated over thousands of years to be lost in years to decades. This constitutes an essentially permanent loss of the productive capacity of ecosystems. Similarly, human modification of river

channels can alter sediment inputs to floodplains and deltas. In the southern U.S., for example, loss of sediment inputs and subsequent soil subsidence led to the disappearance of barrier islands that had previously protected New Orleans from hurricanes (Box 15.1).

Fine particles such as clay and organic matter are particularly important in water and nutrient retention (Chap. 3). They are typically concentrated near the soil surface, where they are vulnerable to loss by erosion. Human activities that foster wind and water erosion, such as deforestation, overgrazing, plowing, or fallowing of agricultural fields, therefore erode the water- and nutrient-retaining capacity of soils much faster than the total loss of soil volume might suggest. Preventing even modestly augmented erosion rates is therefore critical to sustaining the productive capacity of terrestrial ecosystems.

Accelerated soil erosion is one of the most serious causes of global declines in ecosystem services. The erosional loss of fine soil particles is a direct cause of **desertification**, soil degradation that occurs in drylands (Stafford Smith et al. 2009). Desertification can be triggered by drought, reduced vegetation cover, overgrazing, or their interactions (Reynolds and Stafford Smith 2002, Foley et al. 2003a). When drought reduces vegetation cover, for example, goats and other livestock graze more intensively on the remaining vegetation. Extreme poverty and lack of a secure food supply often constrain options for reducing grazing pressure at times of drought because short-term food needs take precedence over practices that might prevent erosion. Wetter regions can also experience severe erosional loss of soil, especially where vegetation loss exposes soils to overland flow. The Yellow River in China, for example, transports 1.6 billion tons of sediment annually from agricultural areas in the loess plateau at its headwaters. Similar erosional losses occurred when grasslands were plowed for agriculture in the U.S. during droughts of the 1930s, creating the dustbowl. Management that maintains vegetation cover, particularly in steep terrain and adjacent to streams, can reduce erosion potential substantially, thereby maintaining the productive potential of terrestrial ecosystems.

Soil erosion from land represents a sediment input to lakes and estuaries. At a global scale, the increased sediment input to the ocean from accelerated erosion is partially offset by the increased sediment capture by lakes and reservoirs. Therefore lakes, including reservoirs, and estuaries are the aquatic ecosystems most strongly affected by terrestrial erosion. Especially in agricultural areas, these sediment and nutrient inputs to aquatic ecosystems can be just as problematic as the loss of productive potential on land (see Chaps. 9 and 13).

## Sustaining Biodiversity

**Biodiversity strongly influences the range of environmental and biotic conditions under which ecosystem processes can be sustained.** Diverse ecosystems contain species that sustain a wide range of ecosystem processes (**effect diversity**) through their use and cycling of soil resources. Diverse systems also contain organisms likely to sustain ecosystem services under a wide range of environmental and biotic conditions (**response diversity**; see Chap. 11; Elmqvist et al. 2003, Suding et al. 2008). This delivery of ecosystem services depends on the kinds of species present (functional composition), genetic diversity within species, species diversity within stands, and landscape diversity across regions (Table 15.2).

Biodiversity in ecosystems that have not been strongly modified by human activities tends to “take care of itself.” Species diversity represents those species that have reached a particular location, can grow and reproduce in that environment, and survive in the face of competition and predation from other species present. If a species disappears from a particular patch, it might recolonize from adjoining patches. Human activities often, however, radically alter the physical and biotic environment through changes in land use and landscape structure or through introduction or elimination of species that govern competitive and trophic interactions among species (Foley et al. 2005). Introduction of rats on islands that historically had no mammals, for example, eliminates flightless birds and many species of native plants (Townsend et al. 2006). Introduction of exotic nitrogen-fixing species into low-nitrogen

environments favors competitive domination by fast-growing weedy species. Predator removal can cause an explosion of herbivore densities that reduce plant diversity. Long-term trends in climate, nutrient deposition, and erosion are now altering the physical environment of the entire planet, altering competitive interactions among species, and often eliminating species that cannot compete effectively under these new conditions. These species losses are occurring much more rapidly than migration or evolution can restore diversity to its former levels. These human effects on biodiversity cumulatively explain why the world is now in the sixth major extinction event in the history of life on Earth (Chapin et al. 2000b). Moreover, loss of species diversity is perhaps the least reversible of the many human-caused global changes. Soil or land cover or the composition of the atmosphere may take thousands of years to return toward its predisturbance state, but extinction is literally forever.

Ecosystem management strongly influences the maintenance or loss of biodiversity. On intensively managed forests or agricultural lands, managers usually deliberately minimize diversity in order to produce uniform stands that can be efficiently managed and harvested. There is a tradeoff, however, between harvest efficiency and the vulnerability of these low-diversity stands to environmental and biotic variability and change (see Chap. 11). These low-diversity stands often require suppression of natural pathogens and disturbances to maintain their productivity. Unintentional human impacts can also alter diversity. Addition of resources such as water or nutrients reduces the number of potentially limiting resources for which plants can compete and therefore the diversity of species that can coexist (Harpole and Tilman 2007).

In less intensively managed ecosystems, biodiversity can be fostered by minimizing the magnitude and extent of novel changes in ecosystems. This reduces the likelihood of loss of species that are well adapted to historical environmental and biotic conditions. For example, minimizing land conversion to agriculture or of fire in tropical forests maintains habitat for native species. Proportional cover of native habitat is a strong predictor of biodiversity in a region. Similarly, preventing the introduction or spread of exotic species

**Table 15.2** Examples of biodiversity effects on ecosystem services. We separate the diversity effects into those due to functional composition, numbers of species, genetic diversity within species, and landscape structure and diversity. Modified from Díaz et al. (2006)

Ecosystem service	Diversity component and mechanism
1. Production by societally important plants	<i>Functional composition:</i> (1) fast-growing species produce more biomass; (2) species differ in timing and spatial pattern of resource use (complementarity allows more resources to be used) <i>Species number:</i> large species pool is more likely to contain productive species
2. Stability of crop production	<i>Genetic diversity:</i> buffers production against losses to pests and environmental variability <i>Species number:</i> cultivation of multiple species in the same plot maintains high production over a broader range of conditions <i>Functional composition:</i> species differ in their response to environment and disturbance, stabilizing production
3. Maintenance of soil resources	<i>Functional composition:</i> (1) fast-growing species enhance soil fertility; (2) dense root systems prevent soil erosion
4. Regulation of water quantity and quality	<i>Landscape diversity:</i> intact riparian corridors reduce erosion <i>Functional composition:</i> fast-growing plants have high transpiration rates, reducing stream flow
5. Pollination for food production and species survival	<i>Functional composition:</i> loss of specialized pollinators reduces fruit set and diversity of plants that reproduce successfully <i>Species number:</i> loss of pollinator species reduces the diversity of plants that successfully reproduce (genetic impoverishment) <i>Landscape diversity:</i> large, well-connected landscape units enable pollinators to facilitate gene flow among habitat patches
6. Resistance to invasive species with negative ecological/cultural effects	<i>Functional composition:</i> some competitive species resist the invasion of exotic species <i>Landscape structure:</i> roads can serve as corridors for spread of invasive species; natural habitat patches can resist spread <i>Species number:</i> species-rich communities are likely to have less unused resources and more competitive species to resist invaders
7. Pest and disease control	<i>Genetic diversity or species number:</i> reduces density of suitable hosts for specialized pests and diseases <i>Landscape diversity:</i> provides habitat for natural enemies of pests
8. Biophysical climate regulation	<i>Functional composition:</i> determines water and energy exchange, thus influencing local air temperature and circulation patterns <i>Landscape structure:</i> influences convective movement of air masses and therefore local temperature and precipitation
9. Climate regulation by carbon sequestration	<i>Landscape structure:</i> fragmented landscapes have greater edge-to-area ratio; edges have greater carbon loss <i>Functional composition:</i> small, short-lived plants store less carbon <i>Species number:</i> high species number reduces pest outbreaks that cause carbon loss
10. Protection against natural hazards (e.g., floods, hurricanes, fires)	<i>Landscape structure:</i> influences disturbance spread or protection against natural hazards <i>Functional composition:</i> (1) extensive root systems prevent erosion and uprooting; (2) deciduous species are less flammable than evergreens

reduces the likelihood of large-scale biodiversity and ecosystem change (Vitousek 1990). Species that have novel ecosystem effects (e.g., nitrogen fixers or highly flammable species) or that have escaped the diseases and predators that control their populations in sites of origin are particularly

likely to have strong impacts on biodiversity. Finally, maintaining natural patterns of disturbance and landscape connectivity sustain populations of all successional stages within a landscape and provide pathways for movement and post-disturbance colonization, as described in the next section.

## Sustaining Variability and Resilience

**Disturbance shapes the long-term fluctuations in the structure and functioning of ecosystems and therefore their resilience and vulnerability to change.** Disturbance is not something that “happens” to ecosystems but is an integral part of their functioning and a key source of temporal and spatial variation in landscapes (see Chap. 12). Species are typically adapted to the disturbance regime that shaped their evolutionary histories. Management that alters this disturbance regime, for example by preventing floods, wildfire, or pest outbreaks, can therefore create conditions to which species are poorly adapted. For example, past efforts to prevent these natural disturbances (e.g., “Smokey-the-Bear” efforts to prevent all wildfires) creates homogeneous patches of late-successional habitat that no longer support early successional species. In addition, late-successional ecosystems are often prone to disease and pest outbreaks (Matson and Boone 1984) that can spread extensively in homogeneous late-successional stands (Raffa et al. 2008). Management that allows small naturally occurring disturbances to occur creates spatial heterogeneity that reduces disturbance spread and therefore the likelihood of large catastrophic disturbances (Holling and Meffe 1996). Allowing small-scale disturbances to occur is often politically challenging, however, because small disturbances sometimes reduce or destroy the economic value of resources that people want to harvest (e.g., forest harvest), create risks in inhabited landscapes (e.g., the wildland–urban interface), or reduce the aesthetic value of familiar patches within a landscape. These tradeoffs are best addressed through long-term social–ecological planning, as discussed later.

The landscape diversity generated by small-scale disturbance creates a mosaic of ecosystems with contrasting structure and species composition. Each stand type is likely to differ in its response to various predictable and unforeseen shocks and disturbances, including historically important disturbances and novel conditions caused by changes in climate, pollution, or novel disturbance regimes (e.g., altered frequency and severity of wildfire or flooding). Thus, just as with genetic or species diversity within stands,

landscape diversity fosters *resilience* to both historical and novel disturbances (Table 15.2; see Fig. 12.8; see Chaps. 12 and 13).

**Management requires a landscape perspective that considers interactions among ecosystems.** A lake cannot be managed sustainably, for example, without considering the nutrient inputs from the surrounding landscape, and forest production can be managed most sustainably as a landscape mosaic by taking account of disturbances such as hurricanes, fire, and logging. The resilience and sustainability of lakes depends on a range of process controls that function at different scales to mitigate the effects of disturbance (Carpenter and Biggs 2009). These process controls include the filtration effects of riparian vegetation and wetlands, the role of game fish in trophic dynamics, and the absorption of nutrients by macrophytes. When these components are intact, landscapes containing lakes can withstand perturbations such as droughts, floods, forest fires, and some land-use change (Turner 2010). Management of landscapes at coarse spatial scales requires different information than management of individual lakes, fields, or forest stands. At coarse spatial scales, monitoring of food webs in lakes is not feasible, so land-use records, remote sensing of lake clarity, knowledge of local residents, and surveys of fishing activity and success provide useful input to models. An important implication of a landscape focus is that it requires the recognition of ecosystem response to multiple driving forces.

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## Applying Ecosystem Principles to Management

**Ecosystem management is the application of ecological science to resource management to promote long-term sustainability of ecosystems and the delivery of essential ecosystem goods and services to society.** The concept was adopted by the U.S. Forest Service in 1992 and has since been developing in theory and application, using a set of common principles (Table 15.3). In this section, we illustrate the application of these principles to selected resource management issues.

**Table 15.3** Attributes of ecosystem management, based on Christensen et al. (1996)

Sustainability	Intergenerational sustainability is the primary objective
Goals	Measurable goals are defined that assess sustainability of outcomes
Ecological understanding	Ecological research at all levels of organization informs management
Ecological complexity	Ecological diversity and connectedness reduces risks of unforeseen change
Dynamic change	Evolution and change are inherent in ecological sustainability
Context and scale	Key ecological processes occur at many scales, linking ecosystems to their matrix
Humans as ecosystem components	People actively participate in determining sustainable management goals
Adaptability	Management approaches will change in response to changes in scientific knowledge and human values

## Forest Management

**The challenge for sustainable forestry is to define the attributes of forested ecosystems that are ecologically and societally important and to maximize these ecosystem services in the face of change.** Forest managers face management challenges that are, in part, logical consequences of the long-lived nature of forest trees (Szaro et al. 1999, Swanson and Chapin 2009):

**Managing forests for multiple ecosystem services involves strong tradeoffs among costs and benefits to different users**, with choices having implications for multiple human generations. Forests provide many ecosystem services, including fuel wood, timber products, water supply, recreation, species conservation, and aesthetic and spiritual values. To support these services, nutrient supply rates must be sufficient to support rapid growth, yet not so high that they lead to large nutrient losses or changes in species composition. The rate at which stands are harvested must be balanced with their rate of regeneration after logging. Species diversity typical of natural mosaics of forest stands should be maintained. The sizes and arrangement of logged patches should provide a semi-natural landscape mosaic with dependable seed sources and patterns of forest edges that allow natural use and movement of animal populations (Franklin et al. 1997). Since it is difficult to anticipate the long-term consequences of different management approaches, there are benefits to using multiple approaches in different areas to meet different user needs and to increase the likelihood that some of these approaches will have favorable long-term outcomes (Bormann and Kiester 2004).

**Managing forests under conditions of rapid change is challenging** because a forest stand is likely to encounter novel environmental and socioeconomic conditions during the life of the individual trees in the stand. Forest ecosystems across the globe face threats from both intentional and inadvertent human impacts, including air pollution, invasive species, and, perhaps above all, global climate change. Because most forest trees will reach maturity under quite different conditions than they begin life, it may be appropriate to reseed forests with a range of genotypes from different climate zones (Millar et al. 2007). This differs from best practices of the past in which locally adapted genotypes of trees were preferred for reforestation.

**Forest conversion to new land uses is a state change that is difficult and time consuming to reverse, given the long regeneration time of forest trees and ecosystems.** Historic and ongoing land use has converted about 40% of preindustrial forest cover to agriculture, built environments, and plantations of a single or narrowly constrained set of species, often exotics (Shvidenko et al. 2005, Foster et al. 2010). Under other conditions, large-scale agricultural abandonment or increased economic value of forests, as for carbon sequestration or aesthetic benefits, can foster **reforestation** or **afforestation** (the regeneration of forests on recently harvested sites or planting of new forests on previously non-forested sites, respectively).

## Fisheries Management

**Formulation of management options for fisheries requires an understanding of ecosystem**

**resilience.** Management options include marine reserves, quota systems, new approaches for setting fishing limits based on population sizes of fish stocks, and economic incentives for long-term population maintenance. Unrestricted fish harvest can reduce sustainability by replacing the natural stabilizing (negative) feedbacks to population changes with amplifying (positive) feedback responses that drive harvested populations to low levels (Berkes et al. 2006, Walters and Ahrens 2009). Supply-and-demand economics and government subsidies, for example, often maintain or *increase* fishing intensity when fish populations decline (Ludwig et al. 1993, Pauly and Christensen 1995). This contrasts with the *decreasing* predation pressure that would accompany a decline in prey population in an unmanaged ecosystem (Francis 1990, Walters and Ahrens 2009).

Management of the North Pacific salmon fishery has instituted a stabilizing (negative) feedback on fishing pressure through tight regulation of fishing activity. Commercial and subsistence fishing are allowed only after enough fish have moved into spawning streams to ensure adequate recruitment. This negative feedback to fishing pressure may contribute to the record-high salmon catches from this fishery after 40 year of management (Ludwig et al. 1993, Walters and Ahrens 2009). Sustaining the fishery also requires protection of spawning streams from changes in other interactive controls. These changes include dams that prevent winter floods (disturbance regime), warming of streams by removal of riparian vegetation of logged sites (microenvironment), species introductions (functional types), and inputs of silt and nutrients in agricultural and urban runoff and sewage (nutrient resources).

A common approach to sustainable management is to harvest only the production in excess of that which would occur when the fish stock is limited by density-dependent mortality, termed **surplus production** (Rosenberg et al. 1993, Hilborn et al. 1995). The existence and magnitude of surplus production depends on whether the remaining fish increase their growth rate or reproductive success when some fish are harvested. This in turn depends on the stability of interactive controls (e.g., physical environment, nutrients, and

predation pressure) and the extent to which these interactive controls respond to changes in fisheries stocks. The major challenge in fisheries management is to estimate surplus production in the face of fluctuating interactive controls and uncertainty in the relationship between these controls and the fish population size. Fisheries biologists actively debate whether any ecosystem is sustainable when subjected to continuous human harvest (Ludwig et al. 1993, Rosenberg et al. 1993, Walters and Ahrens 2009).

## Ecosystem Renewal

**Ecosystem renewal often benefits from the introduction of amplifying (positive) feedbacks that push the ecosystem to a new, more desirable state.** Many ecosystems become degraded through a combination of human impacts, including soil loss, air and water pollution, habitat fragmentation, water diversion, fire suppression, and introduction of exotic species. In degraded agricultural systems and grazing lands, the challenge is to restore them to a productive enough state to provide goods and services to people. In other cases, the goal is to restore the natural composition, structure, processes, and dynamics of the original ecosystem (Christensen et al. 1996). Advances in restoration practices involve identifying the impediments to recovery of ecosystem structure and function and overcoming these impediments with artificial interventions that often use or mimic natural processes and interactive controls (Meffe et al. 2002).

Interventions can be applied to any component of ecosystems, but hydrology, and soil and plant community characteristics are commonly the focus of effort (Box 15.4; Dobson et al. 1997, Meffe et al. 2002). Low soil fertility and organic content are common problems in heavily managed agricultural and pasture systems and in forests or grasslands reestablishing on mine wastes. Fertilizers and nitrogen-fixing trees can restore soil nutrients and organic inputs (Bradshaw 1983). Once soil characteristics are appropriate, plant species can be reintroduced by seeding, planting, or natural immigration (Dobson et al. 1997). The scientific basis for restoration ecology

#### Box 15.4 Everglades Restoration Study

Major human impacts on the natural hydrology of the Everglades ecosystem in the southeastern U.S. began in the early twentieth century. In response to hurricanes, flooding, and the resulting loss of human life and property, the U.S. Army Corps of Engineers built levees, canals, pumping stations, and water control structures that separated the remaining Everglades from growing urban and agricultural areas (Davis and Ogden 1994). The water flow to the remaining “natural” Everglades declined sharply and occurred as pulses of nutrient-rich agricultural and urban runoff regulated by water-control structures. These hydrologic changes caused pronounced fluctuations in water levels and increased the frequency of major drying events (DeAngelis et al. 1998). The survival of many species, including birds, alligators, and crocodiles, depends on reasonable regularity in the rise and fall of water level throughout the year. Since the 1940s the nesting populations of wading birds declined by 90% (Davis and Ogden 1994). Land-use change such as agricultural drainage destroyed many high-elevation, short-hydroperiod wetlands. Eutrophication altered competitive interactions and increased the impacts of invasive species (DeAngelis et al. 1998).

The goals of South Florida ecosystem restoration program include the maintenance of ecological processes such as disturbance regimes, hydrologic processes, and nutrient cycles and maintenance of viable populations of all native species. The U.S. Army Corps of Engineers was charged with both improving protection of Everglades National Park and providing enough water to meet the demands of a large urban and agricultural economy. Planned construction projects include the creation of storm-water

treatment areas to remove phosphorus from the water and to allow increased water diversion into the Everglades (DeAngelis et al. 1998). Additional land is being purchased to provide areas of water storage and a buffer zone between natural areas and the expanding urban zone.

An ecosystem model was developed to evaluate alternative rehabilitation and management options. This spatially explicit landscape model was linked with individual-based modeling of ten higher trophic-level indicator species to provide quantitative predictions relevant to the goals of the Everglades Restoration (DeAngelis et al. 1998). These indicator species, including the Florida panther, white ibis, and American crocodile, differ in their use of the landscape and resources and span a range of habitat needs and trophic interactions (Davis and Ogden 1994). The simultaneous success of all of these species in a restored Everglades would imply health of the overall ecosystem (DeAngelis et al. 1998). The program has adopted a hierarchical modeling approach in which models of higher trophic-level indicator species use information from models at intermediate trophic levels (fish, aquatic macroinvertebrates such as crayfish, and several reptile and amphibian functional types) and lower trophic levels (periphyton, aggregated mesofauna, and macrophytes). These species-specific models are then layered on a landscape Geographic Information System (GIS) model that includes hydrologic and abiotic factors such as surface elevations, vegetation types, soil types, road locations, and water levels (DeAngelis et al. 1998). South Florida provides an example of the incorporation of scientific knowledge of ecosystem processes into long-term state and national ecosystem management efforts.

is actively developing and exploring new challenges (Young et al. 2005). In a rapidly changing world, for example, it may be more practical to target renewal efforts toward ecosystem types that are compatible with emerging climate conditions rather than attempting to restore ecosystems

to a historical state that is increasingly out of equilibrium with its environment (Harris et al. 2006, Choi 2007, Hobbs and Cramer 2008). In this context, **renewal ecology** rather than **restoration ecology** may be the most appropriate framework.

## Management for Endangered Species

**Management for endangered species requires a landscape perspective.** The focus of endangered-species protection has generally been the establishment of protected areas containing populations of the target species and vegetation associated with those species. Establishment of parks is, however, insufficient protection for species when people continue to influence important state factors and interactive controls, such as climate, fire regime, water flows, or species introductions (Hobbs et al. 2010). If climate changes, for example, animals may be trapped inside a park that no longer has a suitable climate or vegetation. Selection of parks that have a range of elevations provides an opportunity for organisms to migrate vertically to higher elevations in response to climate warming. Habitat fragmentation and land-use change also alter the natural linkages among ecosystems inside and outside of parks. Nearly all parks therefore require management to compensate for human impact. The boundaries of Yellowstone National Park, for example, block migration of elk to traditional wintering areas, so winter food supplements must be provided. These winter food supplements in combination with the extirpation of natural predators release the elk population from their natural population controls. Managers must therefore allow hunting or relocation of elk as an alternative mechanism of population regulation. Using intensive management to replace interactive controls, rather than working to sustain the interactive controls, is an expensive, complex, and difficult task, especially when the management has multiple, often conflicting goals (Beschta and Ripple 2009).

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## Socioeconomic Contexts of Ecosystem Management

**Effective ecosystem management requires an integrated social–ecological framework to understand and manage for sustainability in a changing world.** Ecological sustainability cannot be divorced from economic and cultural sustainability. A policy that promotes ecological sustainability at the expense of its human residents

cannot be effectively implemented or sustained. Conversely, programs of economic development that sacrifice long-term ecological or cultural sustainability cannot be sustained over the long term. An emerging challenge is to address regional sustainability in ways that simultaneously consider the ecological, economic, and cultural costs and benefits of particular policies (Berkes et al. 2003, Clark and Dickson 2003, Turner et al. 2003a, Chapin et al. 2009). Design and implementation of policies that foster social–ecological sustainability require close collaboration among many groups, including ecologists, economists, sociologists, anthropologists, policy makers, resource managers, landowners, and industrial and recreational users (Armitage et al. 2007). This comprehensive social–ecological approach (**ecosystem stewardship**) uses both the ecological principles outlined in this book and the principles and understanding developed in many fields of social science. Its objectives, scale, and roles for science and management differ significantly from more traditional management approaches (Table 15.4).

## Meeting Human Needs and Wants

**Success of ecosystem management depends on the capacity of ecosystem services to meet human needs. Human well-being,** or quality of life, reflects a hierarchy of human needs (Maslow 1943): Basic physiological needs such as food and water are the most fundamental, followed by perceptions of safety and security, then sense of belonging through social connections with family and community, then the need for self-esteem and the respect of others, and finally, self-fulfillment through creative actions and efforts to correct social and environmental injustices. Opportunities for social–ecological sustainability increase as more of Maslow’s components of well-being are met. People who lack the resources to meet their basic needs for survival will use local ecosystems to meet these needs, regardless of longer-term consequences. As the hierarchy of human needs is increasingly fulfilled, the opportunities for sustainability are thought to improve. However, many societies that have traditionally depended directly on local harvest actively seek to sustain

**Table 15.4** Differences between steady-state resource management and ecosystem stewardship. Modified from Chapin et al. (2010)

Characteristic	Steady-state resource management	Ecosystem stewardship
Reference point	Historic condition	Trajectory of change
Central goal	Ecological integrity	Sustain social–ecological systems and delivery of ecosystem services
Predominant approach	Manage resource stocks and condition	Manage stabilizing and amplifying feedbacks
Role of uncertainty	Reduce uncertainty before taking action	Embrace uncertainty: maximize flexibility to adapt to an uncertain future
Role of research	Researchers transfer findings to managers who take action	Researchers and managers collaborate through adaptive management to create continuous learning loops
Role of resource manager	Decision maker who sets course for sustainable management	Facilitator who engages stakeholder groups to respond to and shape social–ecological change and nurture resilience
Response to disturbance	Minimize disturbance probability and impacts	Disturbance cycles used to provide windows of opportunity
Resources of primary concern	Species composition and ecosystem structure	Biodiversity, well-being, and adaptive capacity

their lands, even when Maslow’s hierarchy of needs is only modestly met (Dietz et al. 2003, Agrawal et al. 2008, Berkes et al. 2009).

People often consume more resources than are essential to meet their basic needs. Below a per capita income of about \$12,000, the wealth of nations correlates closely with the average happiness of their citizens (Diener and Seligman 2004). Similar correlations are observed within countries. Happiness does not significantly increase, however, once an individual’s basic material needs are satisfied (Easterlin 2001). As people acquire greater wealth above this level, they aspire to achieve even greater wealth, which, in turn, seems to reduce their happiness and overall satisfaction. These findings suggest two basic approaches to achieving a more sustainable match between the flow of ecosystem services and the material needs of society: (1) assure that the basic material needs of poor people are met and (2) reduce the upward spiral of consumption by people whose material needs are already met.

## Managing Flows of Ecosystem Services

**Economic costs and benefits strongly influence the sustainability of ecosystem management,** as discussed earlier in the context of valuation of

ecosystem services. To recap briefly, ecosystem services whose value is uncertain or unknown tend to be undervalued in decisions relative to commodities like wood or fish that can be bought or sold. In addition, greater value is often given to resources that provide immediate benefit than to those resources that are saved for future generations. In traditional economic terms, the value of goods and services received in the future is **discounted** (reduced) by a percentage that reflects the **opportunity cost** (alternative investment) of conserving ecosystem services for the future. Some economists argue that the discount rate of sustaining ecosystem services for use by future generations should be zero, if their use today reduces the capacity of future generations to meet their needs (Heal 2000). Harvest of an old-growth forest, for example, might prevent future generations from enjoying the biodiversity benefits of these forests for several centuries. Ecosystem ecologists can play an important role in decisions involving tradeoffs between present and future generations by documenting the sensitivity of ecosystem services to alternative management actions and their subsequent rates of renewal.

**Natural resources that are privately owned and sold in the market place are often challenging to manage sustainably** because long-term benefits are likely to be strongly discounted,

resulting in greater consideration of short-term costs and benefits. This is particularly true in areas undergoing land development, where rising property values and taxes increase the economic incentives to sell land for development. Privately held timber or ranch lands, for example, are often sold to real estate developers. These land developments not only modify the ecosystem services provided by these lands but also constrain options for maintaining natural disturbance regimes on nearby public lands. Innovative arrangements such as the sale of conservation or agricultural easements, however, allow individuals to continue current land uses at rural tax rates (Ginn 2005, Sayre 2005, Foster et al. 2010). Sometimes, however, decisions continue to follow historical patterns because the **transaction costs** of the time and effort required to learn, negotiate, and enforce new ways of doing things outweigh the benefits to the individual of novel sustainable solutions (Kofinas 2009). Ecosystem managers can sometimes reduce these transaction costs by facilitating the negotiation of conservation and agricultural easements or implementation of other novel sustainable solutions. More generally, policies that align economic incentives with sustainability goals greatly improve the opportunities for sustainable resource use, as in the conservation easements described above. Alternatively, maladaptive subsidies that encourage unsustainable behavior, such as subsidies to fishermen and loggers to maintain harvesting effort when stocks decline below economically profitable levels reduce the likelihood of sustainable resource use.

**Publicly owned natural resources are often managed by government agencies whose responsibility is to manage certain flows of ecosystem services.** Agencies sometimes prioritize specific ecosystem services. In the U.S., for example, many state Departments of Fish and Game or Forestry prioritize the maximum or optimum sustained yield (MSY or OSY, respectively) and efficient production of the natural resources for which they are responsible. In principle, this should allow sustainable use of these resources over the long term. Despite its sustainability goal, management for MSY or OSY tends to overexploit targeted resources because of

overly optimistic assumptions about the capacity to sustain productivity, avoid disturbances, regulate harvesters' behavior, and anticipate extreme economic or environmental events (Holling and Meffe 1996) and ignore the many other benefits that those lands might provide under different management. Ecosystem management that emphasizes multiple use through the delivery of a broader range of ecosystem services is challenging to implement because of tradeoffs among alternative uses. Local timber-based communities, urban residents, and national conservation groups, for example, generally differ in the value placed on different combinations of ecosystem services. Ecosystem ecologists can contribute to well-informed multiple-use resource management by identifying the controls and trends in supporting, provisioning, regulating, and cultural services resulting from different management practices (Meffe et al. 2002).

**Cultural services provided by ecosystems often motivate sustainable use.** Many traditional societies maintain a spiritual or cultural respect for the species and processes that characterize the lands and waters from which they derive their livelihoods (Berkes 2008, Berkes et al. 2009). Some communities maintain sacred groves that meet spiritual needs but also serve as reservoirs of biodiversity that provide seeds and pollinators for surrounding lands (Ramakrishnan 1992, Brown 2003, Tengö et al. 2007). Many ranchers, farmers, fishermen, and urban residents also value the ecosystem services provided by the lands and waters that they use. Provided the right circumstances, local residents can be articulate spokespersons and stewards for sustainable management of these lands (Armitage et al. 2007). On the other hand, local people can also be outspoken advocates of unsustainable harvest policies. The challenge for ecosystem management is to find a balance of uses that supports local livelihoods at a level that is sustainable over the long term. In many cases, people have a **sense of place** for the lands and waters where they grew up or live. This can be as (or more) powerful than economic incentives in motivating sustainable use of land. Ecosystem ecologists can support this sense of place through engagement of local

residents in citizen science and education to learn about the places where they live or of visitors who may value distant places for aesthetic or other reasons. Ecosystem ecologists also have much they can learn about the places they manage from local people based on their observations and cultural knowledge (Berkes 2008).

**Sustainable ecosystem management is not restricted to private or publicly owned lands. Resource-dependent societies often sustainably manage natural resources that they hold in common (common-pool resources) even in the absence of private property or government regulation.** A variety of informal rules for managing **common-pool resources** have evolved in different societies (Dietz et al. 2003, Ostrom 2009). Management of common-pool resources is most likely to be sustainable when

- The resource used in common occurs within clearly defined boundaries and is managed by resource users (e.g., water in a watershed or fish in a coral reef)
- The benefits that users receive are proportional to labor and costs that users spend in sustaining and harvesting the resource
- Users participate in forming and modifying the rules so that no outsider can make arbitrary rules that determine the distribution of the resource among users
- Users (or their representatives) monitor resource use to make sure that no individual harvests more than their share
- Users who violate harvest rules are punished in proportion to the seriousness of the offense
- Users have easy ways to resolve conflicts
- Users have the right to organize if they are dissatisfied with the way the resource is managed

None of these conditions is essential or guarantees that resource use will be sustainable, but each condition increases the likelihood of sustainable resource use. Examples of apparently sustainable management of common-pool resources for decades to centuries include lobster harvest in Maine, subsistence fisheries in many parts of the world, harvest of hay in Switzerland and of bamboo in Japan (Ostrom 1990). There are also many examples of *unsustainable* management of common-pool resources. The circumstances that influence the success or failure of these informal

management systems usually depend on local conditions and history (Ostrom 2007). A corrupt leader, for example, can undermine a system that might otherwise work well. Similarly, privatization or government efforts to regulate locally managed common-pool resources can disrupt sustainable patterns of local control and use. **Open access**, in which common-pool resources can be harvested by anyone without restrictions, as in many open-ocean fisheries, creates conditions that are least likely to allow sustainable management – the tragedy of the commons (Hardin 1968, Berkes et al. 2006).

### Addressing Political Realities

**Many of greatest challenges faced by resource managers reflect the social and political environment in which they work.** Differences among users in goals and values, power relationships, regulatory and financial constraints, personalities, and other social and political factors often dominate the day-to-day challenges faced by resource managers. Social processes are therefore an integral component of ecosystem management. At times of rapid social or environmental change, frameworks for managing natural resources may become dysfunctional, requiring communication with a broader set of users and managers and openness to new ways of doing things. Management organizations that have become bureaucratic may be resistant to change or slow to adjust. Power hierarchies within these organizations may either facilitate or inhibit efforts to manage ecosystems for multiple ecosystems services during times of change.

Political awareness is crucial to ecosystem ecologists who wish to inform policies for sustainability. Only a small fraction of scientific research actually influences policy (Clark and Holliday 2006, Kristjanson et al. 2009). To be effective, science must, first and foremost, be **credible** in the sense that it is “good science” that is grounded in understanding and facts rather than in arguments of how the world should work. Second, it must be viewed as **legitimate** (unbiased and respectful) by multiple user groups rather than being seen as the agenda of a single advocacy

group. This often requires extensive engagement and dialogue with multiple user groups who may have different concerns and views on preferred policy outcomes. Finally, science is most effective when it is **salient**, i.e., presented to the right people at the right time. Scientists often publish their findings in scientific journals without making the extra effort to present it to those managers who are most likely to use the information in a form that is useful for decision making. Also, reports that are published after the window for policy change has closed will not have much policy impact. Some rules of thumb for linking scientific knowledge with action include (Clark and Holliday 2006, Kristjanson et al. 2009):

- Joint definition by scientists and users of the research problems to be addressed.
- Research dialogue and management that leads to “use-inspired science,” i.e., science that improves basic understanding while seeking to provide information that solves problems (Stokes 1997).
- Engagement of boundary organizations (e.g., nongovernmental organizations) that help bridge communication gaps between researchers and policy makers.
- Systems framework that recognizes scientific research as just one piece of a broad set of social–ecological considerations.
- Research designed to facilitate learning rather than knowledge production; this often entails greater risk-taking than most scientific research.
- Emphasis on capacity building with flexibility, often involving networks that develop new strategies and develop local capacity for action.
- Manage asymmetries of power to level the playing field among multiple producers and users of knowledge; this may require reaching out to potentially disenfranchised users.

## Innovation and Adaptive Management

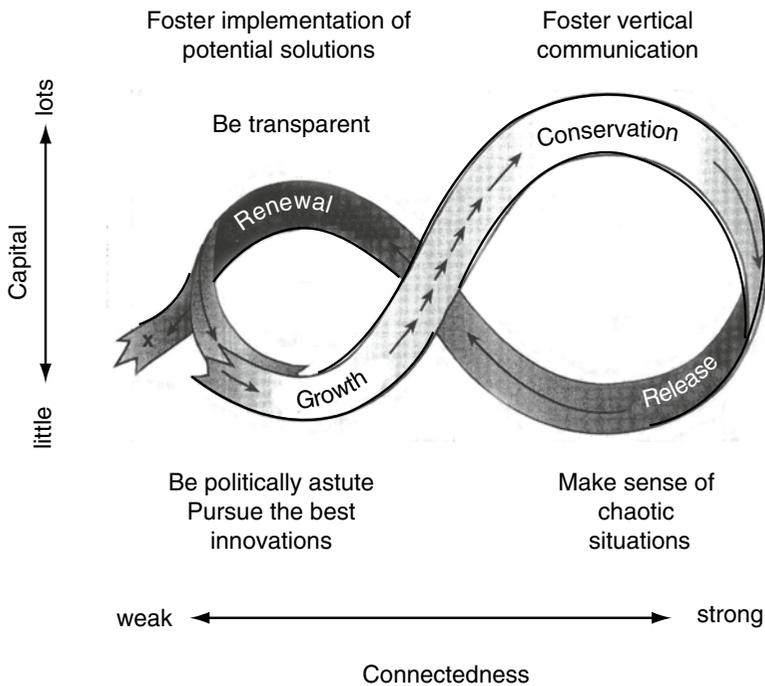
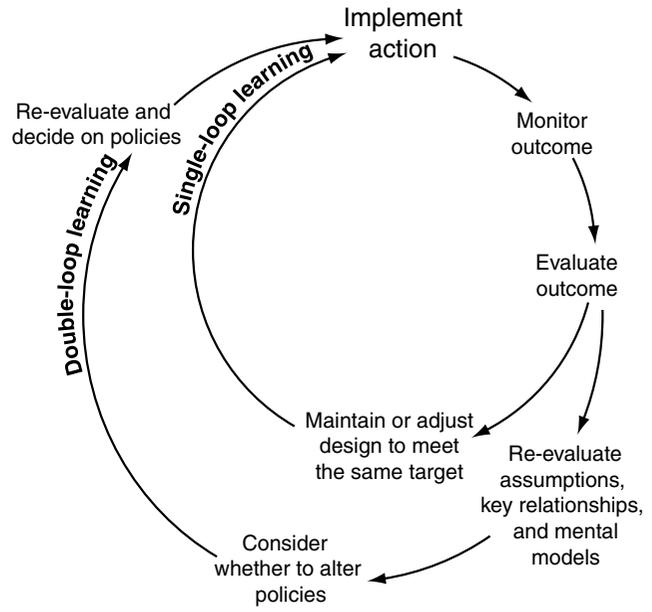
**Adaptive management, involving experimentation in the design and implementation of policies, is central to effective management of ecosystems.** It involves “learning by doing.”

An **adaptive policy** is one that is designed from the outset to test hypotheses about the ways in which ecosystem behavior is altered by human actions. In this way, if the policy fails, learning occurs, so better policies can be applied in the future. Perhaps as a result of frequent management failures and gaps in scientific knowledge, the concept of adaptive management has become central to the implementation of ecosystem management. One advantage of adaptive management stems from the high degree of uncertainty in real-life complex systems (Levin 1999). Instead of delaying timely action due to the lack of certainty, adaptive management provides the opportunity to learn from management experience. The lack of action in the face of uncertainty is a management decision, and it can have ecosystem and societal consequences that are at least as detrimental as actions based on reasonable hypotheses about how ecosystems function. Hypotheses that underlie adaptive management might consider the probabilities of both desired outcomes and ecological disasters (Starfield and Bleloch 1991). A preferred policy, for example, may be one that has a moderate probability of desirable outcomes and a low probability of causing an ecological disaster.

Adaptive management can be applied to both big questions and small ones. **Single-loop learning**, for example, adjusts actions needed to meet a previously agreed-upon management goal, such as changes in harvest levels needed to sustain populations of a particular fish or tree species (Fig. 15.5). **Double-loop learning**, however, requires that managers evaluate the approach they have used previously before taking further action, for example assessing the costs and benefits of managing forests for multiple ecosystem services rather than for a single product (e.g., trees; Armitage et al. 2007, Kofinas 2009).

Double-loop learning requires “out-of-the-box” thinking and innovation. Approaches to stimulating innovation vary with social context (Westley et al. 2006). When conditions are static and management is relatively rigid, innovation can be stimulated by facilitating communication among different levels in the hierarchy (e.g., among practitioners and mid- and upper-level managers) about the nature of problems and

**Fig. 15.5** Single- and double-loop learning. Single-loop learning involves changing actions to meet identified management goals (e.g., modifies harvest rate to conform to specified catch limits), often through trial and error. Double-loop learning includes a reflection process of evaluating underlying assumptions and models that are the basis of defining problems (e.g., revising the indicators and simulation models used to calculate the relationship between fertilizer inputs and crop production based on recent policy outcomes). Reprinted from Kofinas (2009)



**Fig. 15.6** Strategies for effective innovation at different phases of social–ecological disturbance or renewal. Social–ecological systems often go through cycles of growth and development (e.g., ecosystem succession, development of management expertise in an agency), then a conservation phase where conditions are relatively stable, then perhaps a

radical change (release) due to a change in ecological or political environment, then a reorganization in a similar or modified condition (Holling and Gunderson 2002). The strategies that are most effective in stimulating innovation and novelty differ among these phases of the cycle of disturbance and renewal. (Westley et al. 2006)

potential solutions (Fig. 15.6). During times of management crisis, innovation that identifies patterns, explains causes, and suggests potential solution may be particularly helpful. As potential solutions begin to emerge, efforts to assess and promote (with transparency) the most appropriate solutions may lead to greatest progress. Finally, after an agreed-upon solution emerges, politically astute efforts to implement it are particularly helpful (Westley et al. 2006). In any case, adaptive management must work hand in hand with careful monitoring of outcomes. Without that monitoring, there is little chance to learn how interventions have or have not worked and therefore little opportunity to improve them.

### **Sustainable Development: Social–Ecological Transformation**

**Integrated conservation and development projects (ICDPs) seek to address conservation and human livelihood concerns in the developing world.** ICDPs focus equally on biological conservation and human development, typically through externally funded, locally based projects (Wells and Brandon 1993, Kremen et al. 1994, Berkes et al. 2009). In the past, conservation and development projects typically were considered separately, by different organizations, sometimes with conflicting goals and consequences (Sutherland 2000). However, the two directives are more likely to be successful if considered together. The main goal of ICDPs is to link these previously opposing goals. In response to the failure of conservation and development projects to succeed separately, ICDPs emerged in the 1980s and established formal partnerships between conservation organizations and development agencies in an effort to create environmentally sound, economically sustainable alternatives to destructive land-use change (Kremen et al. 1994, Barrett and Arcese 1995, Alpert 1996).

An important objective of ICDPs is to determine the types, intensities, and distribution of resource use that are compatible with the conservation of biodiversity and the maintenance of ecological processes (Alpert 1996). Most ICDPs

therefore have the following characteristics. (1) They link conservation of natural habitats with the improvement of living conditions in the local communities. (2) They are site-based and tailored to specific problems such as impending loss of exceptional habitat. (3) They attract international expertise, local support, and external sources of income, and (4) they adapt to conditions in the developing world such as heavy dependence on natural resources, high population growth, and high opportunity costs of protected areas (Alpert 1996). ICDPs often seek to team a nongovernmental organization, a foreign donor agency, a national agency in charge of forestry, wildlife, or parks with local traditional and official leaders. Projects should couple biological information and scientific knowledge of ecosystem processes with the interests of managers and local communities in their design and implementation.

One major challenge of successful ICDPs is to develop an appropriate research mechanism to collect the scientific data needed to guide the dual objective of conservation and development (Kremen et al. 1994). It is critical to monitor biodiversity and ecosystem processes across space and time and at multiple levels of ecological organization (species, communities, ecosystems, and landscape) and their responses to management (Noss 1990, Kremen et al. 1994). Ecological and socioeconomic indicators can identify the causes and consequences of habitat loss, monitor changes in resource use and harvesting impacts, or evaluate the success of various management programs (Kremen et al. 1994, Barrett and Arcese 1995, Kremen et al. 1998). A successful monitoring program is essential to test the hypothesis that economic development linked to conservation promotes conservation.

In the 1990s, more than 100 ICDP projects were initiated, including over 50 in at least 20 countries in sub-Saharan Africa (Alpert 1996). A review of African projects concluded that ICDPs do not provide a definitive solution to habitat loss, but they can offer medium-term solutions to local conflicts between biological conservation and natural resource use in economically poor, remote areas of exceptional ecological importance (Alpert 1996). Only 16% of World Bank projects

in developing nations have been successful in stimulating both ecological sustainability and human development (Tallis et al. 2008). Limited tourist revenue potential, lack of local management capacity, political unrest, large human populations, customary rights to land or resources enclosed by reserves, or the absence of an official protected area can pose significant impediments to the success of a project (Alpert 1996). The ICDPs most successful in promoting conservation contain significant community participation, which fosters improved community attitudes toward conservation (Brown 2003, Liu et al. 2008, Berkes et al. 2009). As with other kinds of ecosystem management, getting the science right is an essential, but insufficient, step. Over the long run, as we learn from successes and failures, the approaches employed in ICDPs will evolve to address remaining impediments and challenges.

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## Summary

Human activities influence all ecosystems on Earth. Ecosystems are directly impacted by activities such as resource harvests, land conversion, and management and are indirectly influenced by human-caused changes in atmospheric chemistry, hydrology, and climate. Because human activities strongly influence most of Earth's ecosystems, it follows that we should also take responsibility for their care and protection. Part of that responsibility must be to slow the rate and extent of global changes in climate, biogeochemical cycles, and land use. In addition, active management of all ecosystems is required to maintain populations, species, and ecosystem functions in the face of anthropogenic change and to sustain the provision of goods and services that humans receive from them.

State factors and interactive controls exert such strong control over ecosystem processes that changes in these controlling factors inevitably alter ecosystems and reduce the extent to which their current properties can be sustained. Management practices can, however, strongly influence the degree of sustainability. If the goal of management is to enhance sustainability of

managed and unmanaged ecosystems, this requires that state factors and interactive controls be conserved as much as possible and that stabilizing (negative) feedbacks, which contribute to maintaining these controls, be strengthened within and among ecosystems. Directional changes in many of these ecosystem controls heighten the challenge of sustainably managing natural resources and threaten the sustainability of natural ecosystems everywhere.

The ecosystem approach to management applies ecological understanding to resource management to promote long-term sustainability of ecosystems and the delivery of essential ecosystem goods and services to society. This requires a landscape or regional perspective to account for interactions among ecosystems and explicitly includes humans as components of this regional system. Ecosystem management acknowledges the importance of stochastic events and our inability to predict future conditions with certainty. Adaptive management takes actions based on hypotheses of how management will affect the ecosystem. Based on the results of these experiments, management policies are modified to improve sustainability.

Integrated conservation and development projects (ICDPs) apply adaptive management to conservation in the developing world. ICDPs focus equally on biological conservation and human development. The main goal of ICDPs is to link these often previously opposing goals, based on the assumption that local human populations will place immediate socioeconomic security before conservation concerns. A fundamental principle underlying ecosystem management in general, and ICDPs in particular, is that people are an integral component of regional systems and that planning for a sustainable future requires solutions that are ecologically, economically, and culturally sustainable.

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## Review Questions

1. What are the major direct and indirect effects of human activities on ecosystems? Give examples of the magnitude of human impacts on ecosystems.

2. How does the resilience of an ecosystem influence its sustainability in the face of human-induced environmental change? What ecological properties of ecosystems influence their sustainability?
3. Describe a management approach that would maximize ecosystem sustainability. What factors or events are most likely to cause this management approach to fail?
4. What are ecosystem goods and services? How can an understanding of ecosystem services be used in management decisions?
5. What is ecosystem management? What is the role of humans in ecosystems in the context of ecosystem management?
6. What are the advantages and disadvantages of adaptive management as an approach to managing ecosystems?
7. What have integrated conservation and development projects (ICDPs) taught us about the advisability of including humans as components of ecosystems?

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## Additional Reading

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