2 *Ecosystems and Their Services*

Executive Summary

- An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment, interacting as a functional unit. Humans are an integral part of ecosystems.
- A well-defined ecosystem has strong interactions among its components and weak interactions across its boundaries. A useful ecosystem boundary is the place where a number of discontinuities coincide, for instance in the distribution of organisms, soil types, drainage basins, or depth in a water body. At a larger scale, regional and even globally distributed ecosystems can be evaluated based on a commonality of basic structural units.
- Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth.
- Biodiversity is the variability among living organisms. It includes diversity within and among species and diversity within and among ecosystems. Biodiversity is the source of many ecosystem goods, such as food and genetic resources, and changes in biodiversity can influence the supply of ecosystem services.
- People seek many services from ecosystems and thus perceive the condition of an ecosystem in relation to its ability to provide desired services. The ability of ecosystems to deliver services can be assessed by a variety of qualitative and quantitative methods.
- An assessment of the condition of ecosystems, the provision of services, and their relation to human well-being requires an integrated approach. This enables a decision process to determine which service or set of services is valued most highly and how to develop approaches to maintain services by managing the system sustainably.

Introduction

Millions of species populate Earth. The vast majority gain energy to support their metabolism either directly from the sun, in the case of plants, or, in the case of animals and microbes, from other organisms through feeding on plants, predation, parasitism, or decomposition. In the pursuit of life and through their capacity to reproduce, organisms use energy, water, and nutrients. Terrestrial plants obtain water principally from soil, while animals get it mainly from free-standing water in the environment or from their food. Plants obtain most of their nutrients from the soil or water, while animals tend to derive their nutrients from other organisms. Microorganisms are the most versatile, obtaining nutrients from soil, water, their food, or other organisms. Organisms interact with one another in many ways, including competitive, predatory, parasitic, and facilitative ways, such as pollination, seed dispersal, and the provision of habitat.

These fundamental linkages among organisms and their physical and biological environment constitute an interacting and ever-changing system that is known as an ecosystem. Humans are a component of these ecosystems. Indeed, in many regions they are the dominant organism. Whether dominant or not, however, humans depend on ecosystem properties and on the network of interactions among organisms and within and among ecosystems for sustenance, just like all other species.

As organisms interact with each other and their physical environment, they produce, acquire, or decompose biomass and the carbon-based or organic compounds associated with it. They also move minerals from the water, sediment, and soil into and among organisms, and back again into the physical environment. Terrestrial plants also transport water from the soil into the atmosphere. In performing these functions, they provide materials to humans in the form of food, fiber, and building materials and they contribute to the regulation of soil, air, and water quality.

These relationships sound simple in general outline, but they are in fact enormously complex, since each species has unique requirements for life and each species interacts with both the physical and the biological environment. Recent perturbations, driven principally by human activities, have added even greater complexity by changing, to a large degree, the nature of those environments.

Ecosystem Boundaries and Categories

Although the notion of an ecosystem is ancient, ecosystems first became a unit of study less than a century ago, when Arthur Tansley provided an initial scientific conceptualization in 1935 (Tansley 1935) and Raymond Lindeman did the first quantitative study in an ecosystem context in the early 1940s (Lindeman 1942). The first textbook built on the ecosystem concept, written by Eugene Odum, was published in 1953 (Odum 1953). Thus the ecosystem concept, so central to understanding the nature of life on Earth, is actually a relatively new research and management approach.

Tansley's formulation of an ecosystem included "not only the organism-complex, but also the whole complex of physical factors forming what we call the environment" (Tansley 1935:299). He noted that ecosystems "are of the most varied kinds and sizes." The main identifying feature of an ecosystem is that it is indeed a system; its location or size is important, but secondary.

Following Tansley and subsequent developments, we chose to use the definition of an ecosystem adopted by the Convention on Biological Diversity (CBD): "a dynamic complex of plant, animal and micro-organism communities and their nonliving environment interacting as a functional unit" (United Nations 1992:Article 2).

Biodiversity and ecosystems are closely related concepts. Biodiversity is defined by the CBD as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (United Nations 1992:Article 2). Diversity thus is a structural feature of ecosystems, and the variability among ecosystems is an element of biodiversity. The parties to the convention have endorsed the "ecosystem approach" as their primary framework for action. (See Box 2.1.)

For analysis and assessment, it is important to adopt a pragmatic view of ecosystem boundaries, depending on the questions being asked. In one sense, the entire biosphere of Earth is an ecosystem since the elements interact. At a smaller scale, the guiding principle is that a well-defined ecosystem has strong interactions among its components and weak interactions across its boundaries. (See also Chapter 5.) A practical approach to the spatial delimitation of an ecosystem is to build up a series of overlays of significant factors, mapping the location of discontinuities, such as in the distribution of organisms, the biophysical environment (soil types, drainage basins, depth in a water body), and spatial interactions (home ranges, migration patterns, fluxes of matter). A useful ecosystem boundary is the place where a number of these relative discontinuities coincide. At a larger scale, regional and even globally distributed ecosystems can be evaluated based on the commonality of basic structural units. We use such a framework in the MA for the global analysis of ecosystem properties and changes.

The global assessment being undertaken by the MA is based on 10 categories: marine, coastal, inland water, forest, dryland, island, mountain, polar, cultivated, and urban. (See Box 2.2.) These categories are not ecosystems themselves, but each contains a number of ecosystems. The MA reporting categories are not mutually exclusive: their boundaries can

BOX 2.1 The Ecosystem Approach: A Bridge Between the Environment and Human Well-being

The concept of an ecosystem provides a valuable framework for analyzing and acting on the linkages between people and their environment. For that reason, the ecosystem approach has been endorsed by the Convention on Biological Diversity (CBD) and the Millennium Ecosystem Assessment (MA) conceptual framework is entirely consistent with this approach. The CBD defines the ecosystem approach as follows:

> The Ecosystem Approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. Thus, the application of the ecosystem approach will help to reach a balance of the three objectives of the Convention: conservation; sustainable use; and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources. An ecosystem approach is based on the application of appropriate scientific methodologies focused on levels of biological organization, which encompass the essential structure, processes, functions and interactions among organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral component of many ecosystems.

According to the CBD, the term ecosystem can refer to any functioning unit at any scale. This approach requires adaptive management to deal with the complex and dynamic nature of ecosystems and the absence of complete knowledge or understanding of their functioning. It does not preclude other management and conservation approaches, such as biosphere reserves, protected areas, and single-species conservation programs, or other approaches carried out under existing national policy and legislative frameworks; rather, it could integrate all these approaches and other methodologies to deal with complex situations. As described in the CBD, there is no single way to implement the ecosystem approach, as it depends on local, provincial, national, regional, and global conditions.

The conceptual framework of the MA provides a useful assessment structure that can contribute to the implementation of the CBD's ecosystem approach. By way of analogy, decision-makers would not make a decision about financial policy in a country without examining the condition of the economic system, since information on the economy of a single sector such as manufacturing would be insufficient. The same applies to ecological systems or ecosystems. Decisions can be improved by considering the interactions among the parts of the system. For instance, the draining of wetlands may increase food production, but sound decisions also require information on whether the potential added costs associated with the increased risk of downstream flooding or other changes in ecosystem services might outweigh those benefits.

and do overlap. Ecosystems within each category share a suite of biological, climatic, and social factors that tend to differ across categories. More specifically, there generally is greater similarity within than between each category in:

- climatic conditions;
- geophysical conditions;
- dominant use by humans;
- surface cover (based on type of vegetative cover in terrestrial ecosystems or on fresh water, brackish water, or salt water in aquatic ecosystems);
- species composition; and
- resource management systems and institutions.

The factors characterizing ecosystems in each category are highly interrelated. Thus, for example, grasslands are found in many areas where potential evaporation exceeds precipitation. Grasslands, in turn, tend to be used by humans either as rangeland or for agricultural purposes. The areas used for rangeland tend to have pastoral, sometimes nomadic, resource management systems. Thus these factors—high potential evaporation relative to precipitation, grassland cover, use for livestock, and pastoral or nomadic management systems—tend to be found together. (This is typical of the dryland system category in Box 2.2.)

We use overlapping categories in the global MA analysis because this better reflects real-world biological, geophysical, social, and economic interactions, particularly at these relatively large scales. For example, an important issue for ecosystems and human well-being in forested regions relates to the impact of forest harvest or conversion on the timing, quantity, and quality of water runoff. Given the importance of this interaction, it is helpful to analyze an area dominated by forest land cover as a single ecosystem even if it contains some freshwater and agricultural areas within it, rather than analyzing the forest, agriculture, and freshwater ecosystems separately, since this allows for a more holistic analysis of these interactions.

Ecosystem Services

Ecosystem services are the benefits people obtain from ecosystems. This definition is derived from two other commonly referenced and representative definitions:

> Ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human

BOX 2.2 Reporting Categories Used in the Millennium Ecosystem Assessment

Social and ecological systems can be categorized in an infinite number of ways. For the purposes of reporting the global Millennium Ecosystem Assessment (MA) findings, we have developed a practical, tractable, sufficiently rich classification based on 10 systems. Thus, for example, the MA will report on "forest systems," defined to be areas with at least 40 percent canopy (tree) cover. Using this approach, a forest system will contain a variety of different types of ecosystems, such as freshwater ecosystems, agroecosystems, and so forth. But all areas within the boundaries of the forest system as defined here will tend to share a suite of biological, climatic, and social factors, so the system categories provide a useful framework for analyzing the consequences of ecosystem change for human well-being. Because the boundaries of these reporting categories overlap, any place on Earth may fall into more than one category. Thus a wetland ecosystem in a coastal region, for instance, may be examined both in the MA analysis of "coastal systems" as well as in the analysis of "inland water systems."

The following table lists the basic boundary definitions that will be used in the global MA analysis. In a number of cases the MA will also examine conditions and changes in ecosystems with reference to more than one boundary definition. For example, although we use a boundary of 40 percent tree (canopy) cover as our basic definition of the forest category, another widely accepted definition of "forests" is at least 10 percent canopy cover.

Millennium Ecosystem Assessment Reporting Categories

Category	Central Concept	Boundary Limits for Mapping
Marine	Ocean, with fishing typically a major driver of change	Marine areas where the sea is deeper than 50 meters.
Coastal	Interface between ocean and land, extending seawards to about the middle of the continental shelf and inland to include all areas strongly influenced by the proximity to the ocean	Area between 50 meters below mean sea level and 50 meters above the high tide level or extending landward to a distance 100 kilometers from shore. Includes coral reefs, intertidal zones, estuaries, coastal aquaculture, and seagrass communities.
Inland water	Permanent water bodies inland from the coastal zone, and areas whose ecology and use are dominated by the permanent, seasonal, or intermittent occurrence of flooded conditions	Rivers, lakes, floodplains, reservoirs, and wetlands; includes inland saline systems. Note that the Ramsar Convention considers "wetlands" to include both inland water and coastal categories.
Forest	Lands dominated by trees; often used for timber, fuelwood, and non-timber forest products	A canopy cover of at least 40 percent by woody plants taller than 5 meters. The existence of many other definitions is acknowledged, and other limits (such as crown cover greater than 10 percent, as used by the Food and Agriculture Organization of the United Nations) will also be reported. Includes temporarily cut-over forests and plantations; excludes orchards and agroforests where the main products are food crops.

BOX 2.2 continued

Millennium Ecosystem Assessment Reporting Categories

Category	Central Concept	Boundary Limits for Mapping
Dryland	Lands where plant production is limited by water availability; the dominant uses are large mammal herbivory, including livestock grazing, and cultivation	Drylands as defined by the Convention to Combat Desertification, namely lands where annual precipitation is less than two thirds of potential evaporation, from dry subhumid areas (ratio ranges 0.50–0.65), through semiarid, arid, and hyper-arid (ratio <0.05), but excluding polar areas; drylands include cultivated lands, scrublands, shrublands, grasslands, semi-deserts, and true deserts.
Island	Lands isolated by surrounding water, with a high proportion of coast to hinterland	As defined by the Alliance of Small Island States
Mountain	Steep and high lands	As defined by Mountain Watch using criteria based on elevation alone, and at lower elevation, on a combination of elevation, slope, and local elevation range. Specifically, elevation >2,500 meters, elevation 1,500–2,500 meters and slope >2 degrees, elevation 1,000–1,500 meters and slope >5 degrees or local elevation range (7 kilometers radius) >300 meters, elevation 300–1,000 meters and local elevation range (7 kilometers radius) >300 meters, isolated inner basins and plateaus less than 25 square kilometers extent that are surrounded by mountains.
Polar	High-latitude systems frozen for most of the year	Includes ice caps, areas underlain by permafrost, tundra, polar deserts, and polar coastal areas. Excludes high-altitude cold systems in low latitudes.
Cultivated	Lands dominated by domesticated plant species, used for and substantially changed by crop, agroforestry, or aquaculture production	Areas in which at least 30 percent of the landscape comes under cultivation in any particular year. Includes orchards, agroforestry, and integrated agriculture-aquaculture systems.
Urban	Built environments with a high human density	Known human settlements with a population of 5,000 or more, with boundaries delineated by observing persistent night-time lights or by inferring areal extent in the cases where such observations are absent.

life. They maintain biodiversity and the production of ecosystem goods, such as seafood, forage timber, biomass fuels, natural fiber, and many pharmaceuticals, industrial products, and their precursors (Daily 1997b:3).

Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions (Costanza et al. 1997:253).

The MA definition follows Costanza and his colleagues in including both natural and human-modified ecosystems as sources of ecosystem services, and it follows Daily in using the term "services" to encompass both the tangible and the intangible benefits humans obtain from ecosystems, which are sometimes separated into "goods" and "services" respectively.

Like the term ecosystem itself, the concept of ecosystem services is relatively recent—it was first used in the late 1960s (e.g., King 1966; Helliwell 1969). Research on ecosystem services has grown dramatically within the last decade (e.g., Costanza et al. 1997; Daily 1997a; Daily et al. 2000; de Groot et al. 2002).

It is common practice in economics both to refer to goods and services separately and to include the two concepts under the term services. Although "goods," "services," and "cultural services" are often treated separately for ease of understanding, for the MA we consider all these benefits together as "ecosystem services" because it is sometimes difficult to determine whether a benefit provided by an ecosystem is a "good" or a "service." Also, when people refer to "ecosystem goods and services," cultural values and other intangible benefits are sometimes forgotten.

Ecosystem services have been categorized in a number of different ways, including by:

- functional groupings, such as regulation, carrier, habitat, production, and information services (Lobo 2001; de Groot et al. 2002);
- organizational groupings, such as services that are associated with certain species, that regulate some exogenous input, or that are related to the organization of biotic entities (Norberg 1999); and
- descriptive groupings, such as renewable resource goods, nonrenewable resource goods, physical structure services, biotic services, biogeochemical services, information services, and social and cultural services (Moberg and Folke 1999).

For operational purposes, we will classify ecosystem services along functional lines within the MA, using categories of provisioning, regulating, cultural, and supporting services. (See Figure 2.1.) We recognize that some of the categories overlap.

Provisioning Services

These are the products obtained from ecosystems, including:

- *Food and fiber.* This includes the vast range of food products derived from plants, animals, and microbes, as well as materials such as wood, jute, hemp, silk, and many other products derived from ecosystems.
- *Fuel.* Wood, dung, and other biological materials serve as sources of energy.

FIGURE 2.1 Ecosystem Services

Ecosystem services are the benefits people obtain from ecosystems. These include provisioning, regulating, and cultural services that directly affect people and supporting services needed to maintain the other services.

Provisioning Services	**Regulating Services**	**Cultural Services**
Products obtained from ecosystems	*Benefits obtained from regulation of ecosystem processes*	*Nonmaterial benefits obtained from ecosystems*
■ Food	■ Climate regulation	■ Spiritual and religious
■ Fresh water	■ Disease regulation	■ Recreation and ecotourism
■ Fuelwood	■ Water regulation	■ Aesthetic
■ Fiber	■ Water purification	■ Inspirational
■ Biochemicals	■ Pollination	■ Educational
■ Genetic resources		■ Sense of place
		■ Cultural heritage

Supporting Services

Services necessary for the production of all other ecosystem services

■ Soil formation ■ Nutrient cycling ■ Primary production

- *Genetic resources*. This includes the genes and genetic information used for animal and plant breeding and biotechnology.
- *Biochemicals, natural medicines, and pharmaceuticals*. Many medicines, biocides, food additives such as alginates, and biological materials are derived from ecosystems.
- *Ornamental resources*. Animal products, such as skins and shells, and flowers are used as ornaments, although the value of these resources is often culturally determined. This is an example of linkages between the categories of ecosystem services.
- *Fresh water*. Fresh water is another example of linkages between categories—in this case, between provisioning and regulating services.

Regulating Services

These are the benefits obtained from the regulation of ecosystem processes, including:

- *Air quality maintenance*. Ecosystems both contribute chemicals to and extract chemicals from the atmosphere, influencing many aspects of air quality.

- *Climate regulation.* Ecosystems influence climate both locally and globally. For example, at a local scale, changes in land cover can affect both temperature and precipitation. At the global scale, ecosystems play an important role in climate by either sequestering or emitting greenhouse gases.
- *Water regulation.* The timing and magnitude of runoff, flooding, and aquifer recharge can be strongly influenced by changes in land cover, including, in particular, alterations that change the water storage potential of the system, such as the conversion of wetlands or the replacement of forests with croplands or croplands with urban areas.
- *Erosion control.* Vegetative cover plays an important role in soil retention and the prevention of landslides.
- *Water purification and waste treatment.* Ecosystems can be a source of impurities in fresh water but also can help to filter out and decompose organic wastes introduced into inland waters and coastal and marine ecosystems.
- *Regulation of human diseases.* Changes in ecosystems can directly change the abundance of human pathogens, such as cholera, and can alter the abundance of disease vectors, such as mosquitoes.
- *Biological control.* Ecosystem changes affect the prevalence of crop and livestock pests and diseases.
- *Pollination.* Ecosystem changes affect the distribution, abundance, and effectiveness of pollinators.
- *Storm protection.* The presence of coastal ecosystems such as mangroves and coral reefs can dramatically reduce the damage caused by hurricanes or large waves.

Cultural Services

These are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences, including:

- *Cultural diversity.* The diversity of ecosystems is one factor influencing the diversity of cultures.
- *Spiritual and religious values.* Many religions attach spiritual and religious values to ecosystems or their components.
- *Knowledge systems* (traditional and formal). Ecosystems influence the types of knowledge systems developed by different cultures.

- *Educational values*. Ecosystems and their components and processes provide the basis for both formal and informal education in many societies.
- *Inspiration*. Ecosystems provide a rich source of inspiration for art, folklore, national symbols, architecture, and advertising.
- *Aesthetic values*. Many people find beauty or aesthetic value in various aspects of ecosystems, as reflected in the support for parks, "scenic drives," and the selection of housing locations.
- *Social relations*. Ecosystems influence the types of social relations that are established in particular cultures. Fishing societies, for example, differ in many respects in their social relations from nomadic herding or agricultural societies.
- *Sense of place*. Many people value the "sense of place" that is associated with recognized features of their environment, including aspects of the ecosystem.
- *Cultural heritage values*. Many societies place high value on the maintenance of either historically important landscapes ("cultural landscapes") or culturally significant species.
- *Recreation and ecotourism*. People often choose where to spend their leisure time based in part on the characteristics of the natural or cultivated landscapes in a particular area.

Cultural services are tightly bound to human values and behavior, as well as to human institutions and patterns of social, economic, and political organization. Thus perceptions of cultural services are more likely to differ among individuals and communities than, say, perceptions of the importance of food production. The issue of valuing ecosystem services is addressed in Chapter 6.

Supporting Services

Supporting services are those that are necessary for the production of all other ecosystem services. They differ from provisioning, regulating, and cultural services in that their impacts on people are either indirect or occur over a very long time, whereas changes in the other categories have relatively direct and short-term impacts on people. (Some services, like erosion control, can be categorized as both a supporting and a regulating service, depending on the time scale and immediacy of their impact on people.) For example, humans do not directly use soil formation services, although changes in this would indirectly affect people through the impact on the provisioning service of food production. Similarly, climate regulation is categorized as a regulating service since ecosystem changes can have an impact on local or global climate over time scales relevant to human decision-making (decades or centuries), whereas the production of oxygen gas (through photosynthesis) is categorized as a supporting service since any impacts on the concentration of oxygen in the atmosphere would only occur over an extremely long time. Some other examples of supporting services are primary production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

A Multisectoral Approach

Every part of Earth produces a bundle of ecosystem services. (See Box 2.3.) Human interventions can increase some services, though often at the expense of other ones. Thus human interventions have dramatically increased food provisioning services through the spread of agricultural technologies, although this has resulted in changes to other services such as water regulation. For this reason, a multisectoral approach is essential to fully evaluate changes in ecosystem services and their impacts on people. The multisectoral approach examines the supply and condition of each ecosystem service as well as the interactions among them. The MA has adopted just such an approach.

When assessing ecosystem services, it is often convenient to bound the analysis spatially and temporally with reference to the ecosystem service or services being examined. Thus a river basin is often the most valuable ecosystem scale for examining changes in water services, while a particular agroecological zone may be more appropriate for assessing changes in crop production. When looking at interactions among services, the combination of services provided by an ecosystem, or the variety of services drawn on by a society, the question of boundaries becomes more complex. Issues of boundaries, scale, and habitat heterogeneity are important and are dealt with in greater detail in Chapter 5.

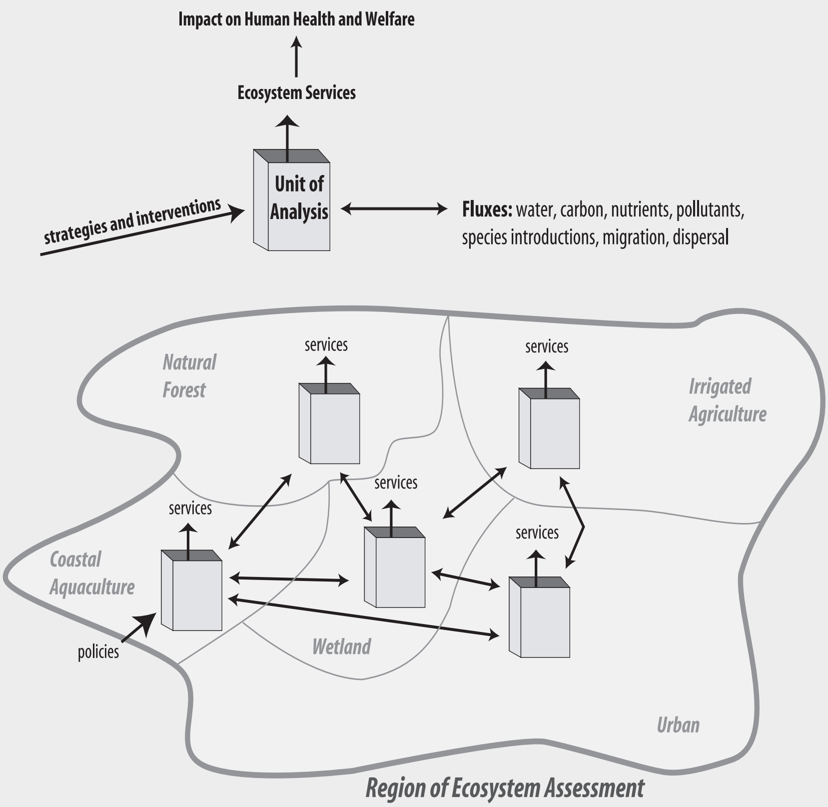
Biodiversity and Ecosystem Services

Habitat modification, invasion, and many other factors are leading to changes in biodiversity across many taxa within most ecosystems. Recently, theoretical and empirical work has identified linkages between changes in biodiversity and the way ecosystems function (Schulze and Mooney 1993; Loreau et al. 2002). The MA will address how ecosystem services are affected by such linkages.

BOX 2.3 Analysis of Ecosystem Services

Any region of Earth produces a set of services that in turn influences human well-being. It also receives flows of energy, water, organisms, pollutants, and other materials from adjacent regions and releases similar materials into those regions. Various strategies and interventions influence the quantity and quality of the services provided.

An ecosystem is typically composed of a number of different regions, such as forest, agriculture, and urban areas, each of which produces a different bundle of services. In an ecosystem assessment, both the production of services from each area and the flows of materials between areas must be assessed.



Among the most important factors identified is the degree of functional redundancy found within an ecosystem. This indicates the substitutability of species within functional groups in an ecosystem such that the impact created by the loss of one or more species is compensated for by others (Naeem 1998). For example, in many ecosystems there are several species that fix nitrogen (known as a functional group of species). If the loss of any one of them is compensated for by the growth of others and there is no overall loss in nitrogen fixation, then there is functional redundancy in that ecosystem.

Some species make unique or singular contributions to ecosystem functioning, however, and therefore their loss is of greater concern (Walker 1992). Small changes in the biodiversity of diverse systems may lead to only small changes in the functioning of an ecosystem, including its production of services, providing no species with unique roles are lost (Jones et al. 1994; Power et al. 1996). But the possibility of significant losses of function increases as more species are lost and as redundancy is reduced—that is, there is an asymptotic relationship between biodiversity and ecosystem functioning. For example, the high diversity of South African fynbos ecosystems ensures steady rates of production because many plant species can compensate for losses by growing when others cannot (Cowling et al. 1994). Greater redundancy represents greater insurance that an ecosystem will continue to provide both higher and more predictable levels of services (Yachi and Loreau 1999).

The MA will seek to evaluate biodiversity and potential declines in biodiversity for different ecosystems under a set of different scenarios for plausible changes in driving forces. This work will extend previous studies that developed scenarios for biodiversity change (Sala et al. 2000). For provisioning and supporting services, the MA will identify which ecosystem functions are associated with these services and link their response to declining biodiversity, using the fundamental asymptotic relationship between biodiversity and ecosystem functioning. Both magnitudes and stability responses to biodiversity loss can be considered using this fundamental relationship.

Ecosystem Condition and Sustainable Use

People seek multiple and different services from ecosystems and thus perceive the condition of an ecosystem in relation to its ability to provide the services desired. The ability of ecosystems to deliver particular services can be assessed separately with various methods and measures. An adequate assessment of the condition of ecosystems, the provision of services, and their implications for human well-being (see Chapter 3) requires an integrated approach. With such an assessment in hand, a decision process (see Chapter 8) can then determine which set of services are valued most highly (see Chapter 6) and can manage the system in a sustainable way.

In a narrow sense, the sustainability of the production of a particular ecosystem service can refer simply to whether the biological potential of the ecosystem to sustain the yield of that service (such as food production) is being maintained. Thus a fish provision service is sustainable if the surplus but not the resource base is harvested, and if the fish's habitat is not degraded by human activities. In the MA, we use the term "sustained yield management" to refer to the management and yield of an individual resource or ecosystem service.

More generally, however, sustainability is used in the context of "sustainable development" to refer to a pattern of development that meets current needs without diminishing prospects for future generations. We use sustainability, and sustainable management, to refer to this goal of ensuring that a wide range of services from a particular ecosystem is sustained.

The MA will consider criteria and methods to provide an integrated approach to ecosystem assessment. The condition and sustainability of each category of ecosystem services is evaluated in somewhat different ways, although in general a full assessment of any service requires considerations of stocks, flows, and resilience.

Condition of Provisioning Services

The flows of provisioning services do not accurately reflect their condition, since a given flow may or may not be sustainable over the long term. The flow is typically measured in terms of biophysical production, such as kilograms of maize per hectare or tons of tuna landings. The provisioning of ecological goods such as food, fuelwood, or fiber, depends both on the flow and the "stock" of the good, just as is the case with manufactured goods. (In economics, "stock" refers to the total merchandise kept on hand by a merchant; in this section, we use "stock" in its economic sense to show how considerations of ecosystem goods can be incorporated into the economic framework of stocks and flows.) The quantity of goods sold by a manufacturer (the flow), for example, is an incomplete measure of a factory's productivity, since it could come from either the production of new goods or the depletion of built-up stocks. Indeed, production of biological resources has often been maintained in the short term at a higher rate than its sustainable yield. In the long term, the production of overharvested resources will fall.

Marine fisheries provide examples of an ecosystem service being degraded even while output has been temporarily maintained or increased by more intensive harvesting. Numerous fisheries around the world have been overharvested, exhibiting a general pattern of rapid growth in landings (production) followed by the eventual collapse of the fishery. (See Box 2.4.) Similar patterns can be found with virtually all other provisioning services.

Agricultural production, for example, can be maintained through the addition of fertilizers and through new crop varieties even while the productive potential of the ecosystem is degraded through soil erosion. Some 40 percent of agricultural land has been strongly or very strongly degraded in the past 50 years by erosion, salinization, compaction, nutrient depletion, biological degradation, or pollution even while overall global food production has increased (WRI et al. 2000). So long as manufactured capital can compensate for losses of the natural capital of the ecosystem, agricultural production can be maintained. In this case, however, manufactured and natural capital are not perfectly substitutable, and once a critical level of soil degradation is reached, agricultural output will decline. A complete accounting of the condition of food production would reveal that it has been degraded because the underlying capability of the ecosystem to maintain production has been degraded.

Historically, it has not been common for environmental or resource assessments to include measures of the productive potential of biological resources when monitoring the condition of the resource. Thus although all countries have considerable information on the production of grain, fisheries, and timber, relatively little is known about the actual condition of these services since the productive potential of the resource has rarely been evaluated. The Pilot Analysis of Global Ecosystems, which was prepared by the World Resources Institute and the International Food Policy Research Institute to assist in the MA design, attempted to provide a more complete assessment of the condition of ecosystem services along these lines (Matthews et al. 2000; Revenga et al. 2000; White et al. 2000; Wood et al. 2000).

Condition of Regulating, Cultural, and Supporting Services

In the case of regulating services, as opposed to provisioning services, the level of "production" is generally not relevant. Instead the condition of the service depends more on whether the ecosystem's capability to regulate a particular service has been enhanced or diminished. Thus if forest clearance in a region has resulted in decreased precipitation and this has had harmful consequences for people, the condition of that regulatory service has been degraded.

BOX 2.4 Collapse of the Atlantic Cod Fishery

The Atlantic cod stocks off the east coast of Newfoundland collapsed in 1992, forcing the closure of the fishery after hundreds of years of exploitation. Until the late 1950s, the fishery was exploited by migratory seasonal fleets and resident inshore small-scale fishers. From the late 1950s, offshore bottom trawlers began exploiting the deeper part of the stock, leading to a large catch increase and a strong decline in the underlying biomass. Internationally agreed quotas in the early 1970s and, following the declaration by Canada of an Exclusive Fishing Zone in 1977, national quota systems ultimately failed to arrest and reverse the decline.

Two factors that contributed to the collapse of the cod stock were the shift to heavy fishing offshore and the use of fishery assessment methods that relied too much on scientific sampling and models based on the relatively limited time series and geographical coverage of the offshore part of the fish stocks. Traditional inshore fishers, whose landings account for one third to one half of the total, had noticed the decline in landings even before the mid-1980s, ahead of the scientists involved in fisheries assessment work but these observations could not be used in stock assessments because of technical difficulties in converting the catches into a suitable form. Finlayson (1994) noted that "science will confer the status of 'valid' only on very specific forms of data presented in a very specialized format."

Northern Cod Off Newfoundland, Canada *(NAFO area 2J3KL)*

Source: Myers et al. 1995.

The evaluation of the condition of cultural services is more difficult. Some cultural services are linked to a provisioning service (such as recreational fishing or hunting) that can serve as a proxy measure of the cultural service. But in most cases no such proxy exists. Moreover, unlike provisioning or regulating services, assessing the condition of cultural services depends heavily on either direct or indirect human use of the service. For example, the condition of a regulating service such as water quality might be high even if humans are not using the clean water produced, but an ecosystem provides cultural services only if there are people who value the cultural heritage associated with it.

Information about the condition of cultural services can be obtained by identifying the specific features of the ecosystem that are of cultural, spiritual, or aesthetic significance and then examining trends in those features. For example, salmon are a totemic or revered species in almost all parts of the world where they are found, and thus the degradation of wild salmon stocks represents degradation of a cultural service provided by the ecosystem. But cultural service information such as this would be difficult to obtain and to quantify: tigers, for instance, remain totemic species even in areas where they have been extinct for decades. Recognizing that the concept of cultural services is relatively new, the MA will explore methods for evaluating the condition and value of these services.

Supporting services maintain the conditions for life on Earth but may affect people only indirectly (by supporting the production of another service, as soil formation supports food production) or over very long time periods (such as the role of ecosystems in producing oxygen). Because the link to human benefits is indirect, as opposed to the other ecosystem services just discussed, a normative scale for assessing the condition of a service is not always practical. For example, primary production is a fundamental supporting service, since life requires the production of organic compounds. But if global primary production were to increase by 5 percent over the next century, it would be difficult to categorize the change as an enhancement or degradation of the service, though it certainly would be a significant change. In such cases the MA will report on the current biophysical state (production, flux, and stocks) of the supporting service.

Variability, Resilience, and Thresholds in Services

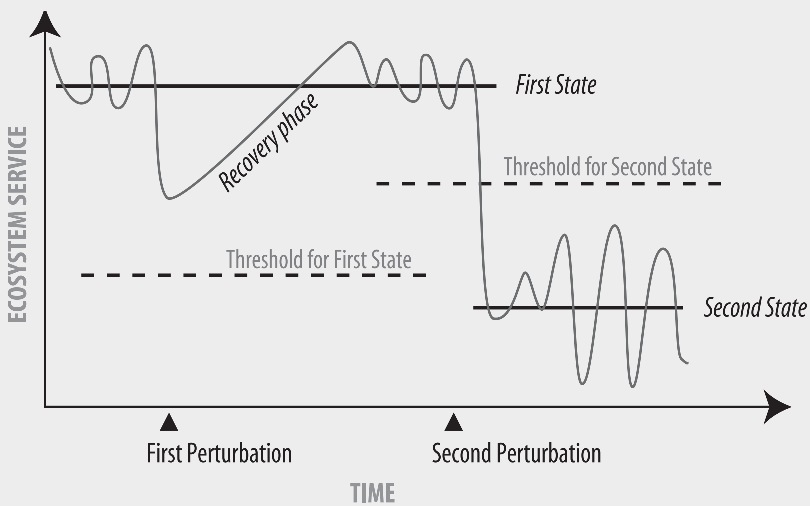
Whenever possible, individuals and governments generally invest in various types of insurance that can buffer human welfare against natural variability. Such investments may be as basic as establishing limited stores of food, medicine, and potable water for disaster relief to more elaborate investments such as building dams, levies, and canals to guard against 100-year floods. How, when, and where to invest in such insurance requires assessing not just mean levels of stocks and flows of ecosystem services but also their dynamics or, more specifically, their variability and stability.

Three characteristics of ecosystem services are important in such an assessment: ecosystem variability, resilience, and thresholds. (See Box 2.5.) There are many other properties of stability in dynamic systems (such as resistance, sensitivity, persistence, reliability, predictability, and so forth), but the MA will limit its focus to these three important and well-studied stability properties.

Variability in ecosystem services consists of changes in stocks or flows over time due to stochastic, intrinsic, and extrinsic factors, all of which must be disentangled to understand system behavior properly. Stochastic variability is due to random or uncontrolled factors creating variability that is often considered background or "white" noise in system behavior.

BOX 2.5 Dynamics and Stability in Ecosystem Services

This figure illustrates the level of provisioning of an ecosystem service that has been perturbed twice. Hypothetically, such a service exhibits stochastic (random or uncontrolled) and inherent variability (fluctuations above and below the two horizontal lines, which represent different system states). The system recovers after the first perturbation, with its resilience being measured by the duration of the recovery phase or return time to its first state. Note that crossing the threshold of the second state does not cause a shift when in the first state. The second perturbation causes the service to cross the second threshold, which leads to a regime shift or catastrophic change to an alternative stable state. The long dashed lines illustrate two thresholds. Only when a system crosses a threshold does it switch to an alternate state.



In contrast, intrinsic (inherent) variability is due to the structural properties of an ecosystem, such as oscillations in systems where predation or disease regulate the number of animals. Examples of extrinsic variability, due to forces outside the system, include seasonality in temperate systems and longer-term climate systems such as El Niño–La Niña cycles.

Resilience is most often considered a measure of the ability of a system to return to its original state after a perturbation—a deviation in conditions that is outside the range experienced over a decade or more, such as a large-scale fire or an unusually severe drought. When the duration of the recovery phase is short in comparison to other systems, the system is considered to be more resilient than the others.

Thresholds or breakpoints in ecosystems represent dramatic, usually sudden (less than a decade) deviations from average system behavior. Such dramatic shifts—also known as regime shifts, catastrophic change, or entering alternative stable states—are often primed by a steady change in internal or external conditions that increases a system's susceptibility to being triggered to enter an alternative state (Scheffer et al. 2001; Carpenter 2003). For example, on a global scale, small, steady increases in global warming may lead to a sudden reorganization of Earth's ocean circulation patterns (Broecker 1997). On a local scale, the increase in grazing animals by ranchers or herders may be responsible for shifts in steppe (grass-dominated) to tundra (moss-dominated) ecosystems (Zimov et al. 1995).

While management goals are often conceived in terms of stocks and flows, reducing system variability and improving predictability are often key parts of management strategies. Examples of such interventions include irrigating crops during droughts, using biocides during pest outbreaks, controlled burning to prevent catastrophic fires, and culling herds to prevent a population explosion. Maintaining forests to prevent erosion or coral reefs to prevent wave impacts in the face of severe storms are examples of managing ecosystems for their insurance value. Ecosystem variability is often addressed through a variety of methods, but management aimed at maintaining ecosystem resilience and avoiding thresholds is sometimes overlooked. In part this is because the mechanisms responsible for such behavior are seldom known, so it is difficult to design management that can deal with resilience or thresholds. In addition, there are no accurate assessments of the probability of perturbations, and the time frame over which such events occur is too long.

The costs to human welfare of ecosystem deviation from its norms of behavior, however, are often severe, thus its inclusion in assessments and management is important. The MA will examine not only magnitudes of ecosystem stocks and flows as they are related to ecosystem goods and services, but also their stability properties. Much of this will be done by extrapolation from expert assessment of paleo records (for instance, climate records derived from ice cores) and historical records (such as long-term fisheries, forestry, or agricultural records) to obtain guidelines on the norms of system variability, resilience, known thresholds, and the environmental stresses that cause ecosystems to be triggered by perturbations to enter into alternative states.

Ecosystem Health and Other Related Concepts

Ecosystem health is a concept that has often been applied to the evaluation of ecosystems (Rapport et al. 1995). This has become a subdiscipline in the life sciences, with its own journals and professional organizations, such as the International Society for Ecosystem Health (ISEH) and the Aquatic Ecosystem Health and Management Society. The term is used sometimes to mean the links between ecosystems and human health. For example, the mission of ISEH is to "encourage the understanding of the critical linkages between human activity, ecological change and human health" (Rapport et al. 1999:83). It is also used to refer to the health of the ecosystem itself: "an ecological system is healthy…if it is stable and sustainable—that is, if it is active and maintains its organization and autonomy over time and is resilient to stress" (Costanza et al. 1992:9).

This concept has generated debate and alternative approaches within the scientific literature (e.g., Reid 1996; de Leo and Levin 1997). One method measures health as a departure from some preferred (often "natural") state. Another, which is consistent with the approach used in the MA to examine the condition of ecosystem services, relates health to the ability of an ecosystem within its surrounding landscape to continue to provide a particular set of services. This considers whether the ecosystem and its external inputs (such as energy or fertilizer) are sustainable in the long term as well as whether the ecosystem can withstand or recover from perturbations (resistance and resilience, respectively) and similar issues.

The concept of ecosystem health is important both within the research community and as a means of communicating information about ecosystems to the general public. Although the MA has not adopted ecosystem health as its primary organizational framework, the concept could be usefully applied within an assessment that used the MA framework.

Several other concepts will also inform the MA without being adopted as organizational frameworks. For instance, ecosystem integrity has been defined as "the maintenance of the community structure and function characteristic of a particular locale or deemed satisfactory to society" (Cairns 1977:56) or "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having species composition, diversity, and functional organization comparable to that of natural habitats of the region" (Karr and Dudley 1981:171). Another example is the "ecological footprint," which expresses the impact of human activity on ecosystems in terms of areas required to provide the services used by an individual or community.

Substitution of Services

Substitutes are available for some ecosystem services, although often the cost of a technological substitution will be high and it may not replace all the services lost. For example, water treatment plants can now substitute for ecosystems in providing clean drinking water, although this may be expensive and will not overcome the impacts of water pollution on other components of the ecosystem and the services they provide. Another outcome of substitution is that often the individuals gaining the benefits are not those who originally benefited from the ecosystem services. For example, local coastal fish production can be replaced by shrimp aquaculture in tropical regions, but the individuals making a living from capture fisheries are not those who would profit from the new shrimp aquaculture facilities.

Therefore, a full assessment of ecosystems and their services must consider:

- information on the cost of a substitute,
- the opportunity cost of maintaining the service,
- cross-service costs and impacts, and
- the distributional impacts of any substitution.