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CHAPTER 3

ECOSYSTEM SERVICES

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A human being is part of the whole, which we call the "Universe"; a part limited in time and space. He experiences himself, his thoughts and feelings as something separated from the rest, a kind of optical delusion of his consciousness. This delusion is a kind of prison for us, restricting us to our personal desires and affection for a few persons nearest us. Our task must be to free ourselves from this prison by widening our circle of compassion to embrace all living creatures and the whole of nature in its astonishing beauty.

—ALBERT EINSTEIN, *Ideas and Opinions*

Earth's mosaic of ecosystems—forests, grasslands, wetlands, streams, estuaries, and oceans—when functioning naturally, provides materials, conditions, and processes that sustain all life on this planet, including human life. The benefits that all living things obtain from ecosystems are called "ecosystem services." Some are very familiar to us, such as food and timber that are essential for our lives and important parts of the global economy. What are equally important, but certainly less well recognized, are the array of services delivered by ecosystems that do not have easily assigned monetary values but that make our lives possible. These include the purification of air and water, the decomposition of wastes, the recycling of nutrients on land and in the oceans, the pollination of crops, and the regulation of climate.

Ecosystem services are generated by a complex of natural cycles, ranging from the short life cycles of microbes that break down toxic chemicals to the long-term and planetwide cycles of water and of elements such as carbon and nitrogen that have sustained life for hundreds of millions of years. Disruption of these natural cycles can result in disastrous problems for human beings. If, for example, the natural services that result in the control of pest populations ceased—that is, if the life cycle of some natural pest enemies were altered, or if they were eliminated in some areas—there could be devastating crop failures. If populations of bees and other pollinators crashed, society could face similar dire consequences. If the carbon cycle were badly disrupted, rapid climate change could threaten whole societies. We tend to take these services for granted and do not generally recognize that we cannot live without them, nor can other life on this planet.

The ecosystems of the world deliver their life-sustaining services for free, and in many cases, they involve such complexity and are on a scale so vast that humanity would find it impossible to substitute for them. In addition, we often do not know what

(left)
Hand Pollination of Apple Blossoms in Nepal. Bees in Manaslu County, at the border between China and Nepal, have gone extinct, forcing people to pollinate apple trees by hand. It takes twenty to twenty-five people to pollinate 100 trees, a task that can be performed by one bee colonies. (From Farooq Ahmad and Uma Patrap, International Center for Integrated Mountain Development, Nepal.)

species are necessary for these services to work, or in what numbers and proportions they must be present.

As the world's human population grows and nonsustainable, per-capita consumption of all kinds of materials increases, ecosystems are being degraded and their capacity to deliver their services is being compromised. The degradation of the world's ecosystems is a "quiet crisis," largely hidden from view, but the consequences of this degradation are potentially catastrophic for human beings.[1] In this chapter, we review the character of ecosystem services, present examples of current work that attempts to provide an economic valuation of these services, and discuss how human activity is threatening them.

The Character of Ecosystem Services

Ecosystems services can be divided into four major categories: provisioning, regulating, cultural, and supporting. For the purposes of this chapter and this book, we look at these services predominantly from a human perspective. *Provisioning services* are the products obtained from ecosystems and include foods and medicines. *Regulating services* are the benefits people obtain from ecosystem controls of climate, plant pests and pathogens, animal diseases (including those that affect humans), water quality, soil erosion, and much more. *Cultural services* are the nonmaterial benefits that people obtain from ecosystems: recreational, aesthetic, spiritual, and intellectual. And *supporting services* are those necessary for the production of all other ecosystem services and include the production of new organic matter by plants through photosynthesis (called "primary production") and the cycling of life-essential nutrients such as carbon, nitrogen, phosphorus, and other elements required for the chemistry of life.

PROVISIONING SERVICES	REGULATING SERVICES	CULTURAL SERVICES
Products obtained from ecosystems	Benefits obtained from environmental regulation of ecosystem processes	Nonmaterial benefits obtained from ecosystems
• food • fuel wood • fiber • medicines	• cleaning air • purifying water • mitigating floods • controlling erosion • detoxifying soils • modifying climate	• aesthetics • intellectual stimulation • a sense of place

SUPPORTING SERVICES

Services necessary for the production of all other ecosystem services

- primary productivity
- nutrient cycling
- pollination

Figure 3.1. A Sampling of Ecosystem Services.

BOX 3.1

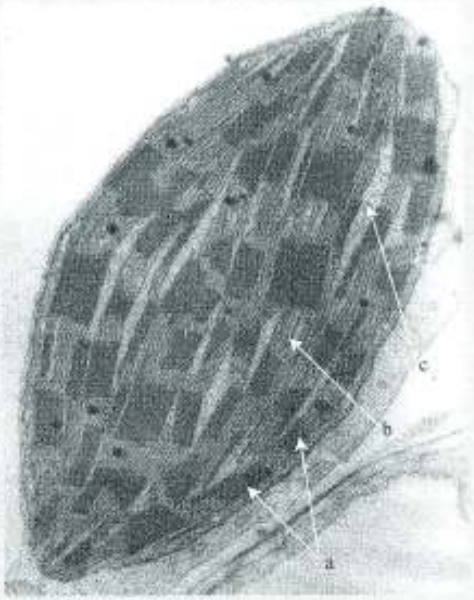
Microbial Ecosystems: Editors' Note

Although the accepted concept of what an ecosystem is, and the one we use in this chapter and throughout this book—that an ecosystem is the sum total of all the organisms in a specific environment and their interactions with each other and with the nonliving components of that environment—includes microbes, scientists generally define ecosystems in macroscopic terms, and primarily by the plants and animals they contain, for these are what we see and what we know best. But it is becoming increasingly clear that most biodiversity on Earth is microbial, that microbes mediate many ecosystem services that sustain life,[a] and that possibly no multicellular organism exists without one or more microbial species living symbiotically on it and/or in it, some of which are necessary for its survival. (Symbiosis is the interaction between two organisms that are living together in an intimate association—this can be mutualism, where both organisms benefit from this interaction; commensalism, where one organism benefits and the other is not affected; or parasitism, where one organism benefits at the expense of the other.)

There is also a wider appreciation that there is another kind of symbiosis at work as well, one that involves the relationship between whole cells and what are called organelles within them, some of which had originally been independent organisms, such as chloroplasts. In converting energy from the sun by photosynthesis and in storing it, all plants depend on chloroplasts. It has become clear that chloroplasts were originally cyanobacteria, which over time, and on several different occasions, were incorporated as integral parts of early algal and plant cells hundreds of millions of years ago. Carl Woese, who devised the three-domain model for classifying life on Earth (see figure 1.4 in chapter 1), is credited with some of the early molecular work showing both chloroplasts and mitochondria to be bacterial in origin.[b,c] Chloroplasts possess their own DNA and replicate independently of the cells they inhabit, although much of their genome now resides within their host cell's nuclei. Starting in the 1960s, Lynn Margulis championed into widespread acceptance the theory that early prokaryotic organisms became organelles in eukaryotic cells, greatly expanding upon an idea that had first been proposed in the late nineteenth century by the German scientist Andreas Schimper.[d]

A similar story can be told about mitochondria, the energy factories that fuel almost all modern plant and animal cells. These mini power generators were originally primitive bacteria that similarly joined with larger cells and became essential plant and animal cellular organelles. Mitochondrial DNA reflects its bacterial origins: it is circular (whereas our eukaryotic DNA is linear), it uses a bacterial type of apparatus and code book to be translated into proteins, and its composition resembles bacterial DNA much more than it does that from multicellular organisms.[e] In spite of these differences, mitochondria have woven their way into the fabric of the cells they inhabit. As with chloroplasts, much of their DNA has been transferred to their cells' nuclei, a place that may be safer for genetic material to reside and where its replication can be completed with greater fidelity, and like chloroplasts, mitochondria replicate independently.[f]

One feature that is of great interest in animals that reproduce sexually is that because some of their mitochondrial DNA is confined to the cytoplasm, it is

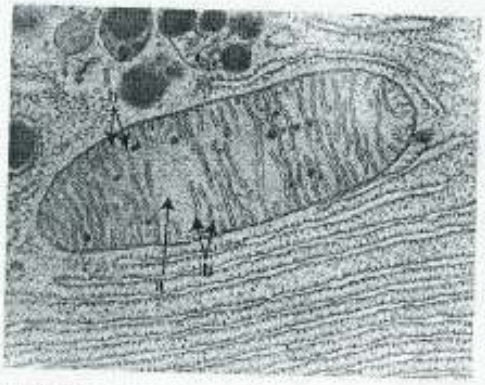


Chloroplast Inside a Higher Plant Cell: Electron Micrograph of a Chloroplast in Cross Section. (a) These flattened hollow disks, each of which is called a thylakoid, together form a stack called a granum. Chlorophyll molecules in the thylakoid membranes initiate the photosynthetic process when they absorb photons from sunlight. (b) Lamellae, the membrane structures that connect the thylakoids from granum to granum. (c) Stroma, the semifluid material that contains the chloroplast's DNA, as well as RNA and enzymes and is the site where carbon dioxide is transformed into glucose and where chloroplast proteins are made. (© Imperial College London; electron micrograph taken by A.D. Greenwood, early 1970s, Department of Botany, Imperial College, print given by J. Barber and A. Telfer; www.bio.ic.ac.uk/research/field/expertise/chloroplast.html.)

contained in the ovum but not in sperm. As a result, one can begin to trace the maternal lineage of an offspring by analyzing its mitochondrial DNA. This is being done to trace the origins of some human populations. Using mitochondrial DNA, for example, it has been possible to trace some 40 percent of all present day Ashkenazi Jews to four maternal lineages who lived in Europe 3000 years ago.[g]

The field that encompasses these insights about the interrelationships among microbial organisms and the multicellular organisms they inhabit, a field that owes much to the work of Thomas Brock (the discoverer of *Thermus aquaticus*—see chapter 5, page 179) in the 1960s and the Dutch microbiologist Martinus W. Beijerinck decades earlier, has been called "microbial ecology," and it is currently in a state of explosive growth as a discipline. From this field a new concept is emerging, where entire ecosystems can be individual organisms themselves, or even their organ systems or portions of them, and the inhabitants of these "ecosystems" are largely microbes (although other organisms such as mites occupy them as well)—bacteria, archaea, fungi, algae, protozoa, and viruses. The importance of this way of thinking about ecology cannot be overstated.

- It illustrates that multicellular life on Earth may exist only in association with communities of microbes and that there may be no such thing as a totally independent multicellular organism.



Transmission Electron Micrograph of a Mitochondrion in Cross Section from a Human Pancreatic Cell. (a) The mitochondrial matrix is the space within the inner membrane of the mitochondrion that contains mitochondrial DNA. The citric acid cycle, or Krebs cycle, in which a cell can produce energy from glucose and oxygen, takes place here. (b) Cristae, the folds in the mitochondrial inner membrane, are where electron transport takes place, a process that is a eukaryotic cell's most efficient means of production of adenosine triphosphate, or ATP. ATP is the principal energy storage molecule for all cells. (Photo by Keith R. Porter. © Photo Researchers, Inc.)

- It raises interesting questions about the definition of a species, which assumes that each organism contains only a single genome. Joshua Lederberg, who shared the 1958 Nobel Prize in Physiology or Medicine, has suggested, for example, that the human genome should perhaps include the collective genomes of all of our resident microbes, our so-called microbiome.[h]
- It leads to a deeper understanding about health and disease in animals and plants, including in ourselves, our livestock, and our crops.
- It provides a fuller picture of how immune systems work, where resident beneficial microbes, accepted as "self" as opposed to being rejected as "nonself," may help regulate the development of immune system components, such as Paneth cells in the human small intestine, and trigger their responses (see below).
- It suggests that in our attempts to assess the impacts of environmental changes on organisms, we need to take into account how those changes will affect not only the external environment of organisms, but also their internal environments.
- It makes clear the vital connections we humans, as well as all other multicellular organisms, have with the microbial world, with which we have co-evolved.
- It calls into question the wisdom of such practices as using antibiotic resistance genes in genetically modified foods or of giving antibiotics indiscriminately to aquacultured organisms and to livestock.
- And it challenges the long-held notion that microbes are mostly harmful and that we should attempt to rid ourselves and our immediate surroundings of them, such as by the use of antibacterial soaps and personal hygiene products, actions that are both futile and potentially unhealthy.

In addition to examples presented elsewhere in this book, such as the relationships of vascular plants with their mycorrhizal fungi and of legumes with their nitrogen-fixing bacteria (as detailed in chapter 8), models of "microbial ecosystems" in multicellular organisms are many. Perhaps the best known are the ruminants, such as cows and goats, which possess an organ called a rumen that is filled with billions of anaerobic bacteria, anaerobic fungi, and ciliated protozoa (which themselves have hydrogen-utilizing, methane-generating bacteria within them). These complex microbial communities carry out the process of digesting cellulose and other polysaccharides, breaking these compounds down into simpler sugars that ruminants can then absorb in their intestines.

Wood-eating termites are also dependent on microorganisms. They have flagellated protozoa in their intestines that, in turn, are living symbiotically with many different types of bacteria that surround them and live within them, all of which serve to break down the indigestible components of wood—lignin and cellulose—into digestible compounds for the termite. New studies of bacteria in the gut of the termite *Reticulitermes speratus* have identified more than 300 different species in each individual, and there are estimates that the number may be as high as 700!

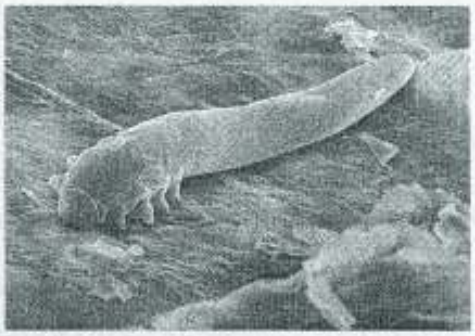
Corals depend on their resident zooxanthellae, microscopic photosynthesizing organisms that provide them with oxygen and nutrients, to survive.[1] Without them, corals appear "bleached" and become vulnerable to fatal infections. The larvae of some oysters and barnacles will not settle and metamorphose into adults until they are colonized by specific bacteria. And cocoa trees are protected from certain fungal diseases by the presence of other fungi that live within their tissues.[2]

We, too, are colonized by a vast, dynamic, and complex world of microbes—on our skin and our eyes, and in all our organs that communicate with the outside world, such as our ears, mouth, nose, trachea, lungs, gastrointestinal tract, and vaginal canal. The number of bacteria in our intestines alone is on the order of 100 trillion, which is about ten times the total number of human cells in our bodies, and these bacteria together are thought to contain 100 times more genes than the entire human genome.[3] Let us look briefly at three of these "ecosystems."

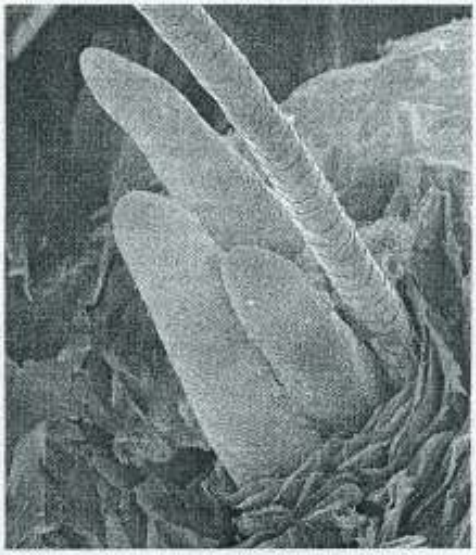
SKIN

Our skin is heavily populated with a wide assortment of bacteria, fungi, and mites, the microscopic arthropods that live in our sebaceous (oil) glands and hair follicles. Different regions of the skin have different numbers of microbial flora. For example, the moist areas of our armpits and the spaces between our toes may harbor as many as 10 million bacteria per square centimeter (about 65 million per square inch), whereas dry areas such as our forearms may contain only one hundred thousandth that number. It is as if one were comparing a rainforest with a desert.[1] And the species themselves may also differ from one skin environment to another.

One recent study of skin microbes on the forearms of six healthy people identified a total of 182 bacterial species belonging to 91 genera. There was a great deal of variation from one person to another, with only four species found on all six subjects. Forearm skin microbial populations also changed over time, with many of the original species no longer present, being replaced by others, when the subjects were tested again 8 to 10 months later.[4] Some skin microbes have been found



Electron Micrograph of a Hair Follicle Mite. Hair Follicle Mites (*Demodex folliculorum*) are thought to be present in a large proportion of people. They live, generally unnoticed, mostly in short hair follicles, such as in those of eyelashes and eyebrows. They also live in the nose and ears, where they feed on secretions and cellular debris. Besides *D. folliculorum*, another skin mite species, *Demodex brevis*, inhabits sebaceous or oil glands in our skin. Whether these mite species play a beneficial role for us under normal conditions, for example, by ingesting dead cells and microbes, is not known. They are found in greater numbers in patients with various skin diseases, but it is not clear whether their increased populations are a consequence, rather than a cause, of these conditions. (Photo © Andrew Syred, Microscopix Photolibrary. Data source: B. Baima and M. Sticherling, Demodicidosis revisited. *Acta Dermato-Venereologica*, 2002;82(1):3.)



Three Follicle Mites Burrowing into a Hair Follicle. (© Andrew Syred, Microscopix Photolibrary.)

Scanning Electron Micrograph of a Subgingival Microbial Community in the Human Mouth. Here we see biodiversity of an oral biofilm demonstrating at least three different bacterial species—two types of bacilli, the rod-shaped organisms (one longer and of greater diameter in cross section than the other), and a type of coccus, or ball-shaped bacterium. (From Ziedonis Skobe, Forsyth Institute.)

to secrete antimicrobial compounds, such as the bacteriocins,[5] that may complement the action of others on the skin, such as psoriasin, a peptide produced by human epithelial cells that has the ability to control the growth of certain Gram-negative bacteria. But despite these and other new insights about microbes that live on our skin, relatively little is known about their diversity or about the role they play in maintaining skin health or in causing disease.

MOUTH

The "ecosystem" of the human mouth has been much better studied than that of the skin, chiefly by Sigmund Socransky, Bruce Paster, Anne Haffajee, and their colleagues at the Forsyth Institute, a dental research center in Boston. Following observations made by the Dutch microscopist Anton van Leeuwenhoek, who studied scrapings of plaque from his own mouth in 1683 and made what may be some of the first drawings of bacteria, these researchers have estimated (based on 16S rRNA studies—see chapter 1, page 10) that there are more than six billion microbes in the human mouth, comprising more than 700 species.[6] Almost all of these are bacteria, but there are also archaea, fungi, amoebas, and viruses. We focus here on the bacteria, for they have been the best characterized.

Each person is thought to have a characteristic set of oral microbes, and each part of the mouth—the tongue, soft palate, gums, and teeth, for example—shows a different composition. The subgingival space, that gap between the base of teeth and the inside of the gums, has been the most extensively studied region, because of its role in periodontal disease, a condition of gum inflammation that can result in tooth loss. The loss of teeth is a significant public health problem worldwide, especially for older populations. Almost three in ten adults older than age 65 in the United States, for example, have lost all of their teeth, primarily because of periodontal disease and tooth decay.[7] Understanding the role that gum microbes play in periodontal disease takes on added importance because of growing evidence that periodontal infections may be associated with atherosclerotic vascular disease, including of the coronary arteries.[8]

A biofilm, consisting of layers of microbes held together by a mucus matrix, coats the mouth's tissues. In the subgingival space, one type of biofilm covers teeth and forms dental plaque; another lines the inside of the gums. One could consider then that not only is the mouth itself an "ecosystem," but so are its various regions, as well as the microenvironments within these regions, each of which contains a different array of microorganisms. These biofilms are extremely resistant to physical removal, such as by dental flossing and tooth brushing, rapidly reestablishing themselves. They can also be highly resistant to antibiotics. Subgingival biofilms are firmly attached to the gums and the teeth and serve to protect them from disease by preventing pathogenic bacteria and other organisms from gaining a foothold. Some commensal oral bacteria have also been found to secrete antimicrobial toxins that kill pathogens.[9,10] Others have been shown to stimulate human epithelial cells lining the gums to produce their own antimicrobial peptides, known as beta-defensins.[5] Studies are under way to determine whether specific species of bacteria and other microbes in these biofilms are associated with specific diseases such as periodontal disease (in which, e.g., some archaea have been shown to play important roles)[8,11] and oral cancers,[12] and whether regular screening of one's oral flora may serve as an early indicator for these diseases.

INTESTINE

There has also been intense interest in the microbial organisms of the human intestine, where the vast majority of the microbes in our bodies reside. Molecular studies based on the same rRNA techniques used with oral bacteria, along with what is called "fluorescent in situ hybridization" (which identifies DNA sequences by attaching fluorescent antibodies to them), have revealed that there are on the order of 800 distinct microbial species, most of which are bacteria, that live in our small and large bowels, comprising thousands of strains or subspecies.[1] Various archaea, viruses, yeasts,

and protozoa also reside in our intestines, with estimates, for example, that there are some 1,200 different types of viruses alone in our feces.[7] The true extent of the diversity of these other organisms, however, remains unknown. (We should note here that debate surrounds whether rRNA studies accurately measure the number of different microbial species that actually reside in specific environments. Knowing whether a given piece of rRNA represents a normal resident of an individual's bacterial community, or whether it was, in the case of the human bowel, e.g., ingested on a piece of food, is difficult to decipher, as is determining whether the bacterium identified is actively functioning in the microenvironments in which it is discovered.) The composition of these intestinal communities has been found to differ not only between individuals, but between different regions of the intestine in the same individual, and between the luminal (the interior space) and mucosal (the surface lining) areas in the same regions.[8]

What they are all doing there is a question that is beginning to occupy a large number of researchers around the world. Some of the services provided by intestinal microbiota are clear. For one, it has long been known that some intestinal bacteria help us break down otherwise indigestible polysaccharides, complex carbohydrates found in plants, into easily absorbed sugars. They also produce vitamins for us, such as vitamin K (as well as very small amounts of the B vitamins—B_{12}, folate, and thiamin).[9] While we obtain some vitamin K from a number of foods, including leafy greens and other vegetables, our main source comes from bacteria in our intestines. Vitamin K is a key co-factor in pathways that control blood clotting and in the formation of human bone through its action on a protein called osteocalcin.

Research on mice raised with sterile intestines has shed further light on some of the roles played by our intestinal flora. Germ-free rodents must consume around 30 percent more calories to maintain the same body weight compared with normal animals. They are also more susceptible to infection.[10] Investigators who added *Bacteroides thetaiotaomicron* (a bacterium that is 1,000 times more abundant in our intestines than the much more widely studied *E. coli* [see section on *E. coli* in chapter 5] and that comprises some 25 percent of all our intestinal bacteria) to the intestines of germ-free mice have discovered several remarkable things. *B. thetaiotaomicron* has been found to monitor concentrations in our guts of a simple sugar called fucose that it uses for energy and to signal our intestinal cells to manufacture more of this sugar when supplies are low. In return, *B. thetaiotaomicron* performs an array of essential "ecosystem services." For one, the bacteria are major players in the breakdown of polysaccharides (in fact, much of the bacterium's genome, sequenced in 2003, is devoted to this process).[11] They also help form the protective layer of mucus coating intestinal epithelial cells, which provides both a physical barrier, preventing these cells from being injured, and which, along with the presence of tight cellular junctions, blocks bacteria from crossing the single-cell-thick epithelial layer to invade other tissues.[12,13] *B. thetaiotaomicron* may protect our bodies from infections in others ways, as well, by interacting with special cells in the small intestine called Paneth cells that are known to secrete a variety of antimicrobial compounds such as defensins (which are thought to help fight food-borne and water-borne bacterial infections);[14] by competing directly with potential pathogens for space and nutrition, thus preventing their colonization; and by producing their own antimicrobial substances, including lactic acid, hydrogen peroxide, and potent antimicrobial peptides such as bacteriocins. Finally, *B. thetaiotaomicron* helps stimulate the growth of new blood vessels, a process called angiogenesis, crucial to the intestines' ability to absorb nutrients.[15] Studying this angiogenic role of *B. thetaiotaomicron* may lead to new insights about how human intestinal cancers form and how to treat them.

Given that we and all other organisms on Earth live in a world composed primarily of microbes with which we have co-evolved complex and dynamic interdependent relationships, it is critically important that we enlarge our definition of ecosystems to include them. By this perspective, ecosystems exist at multiple levels of organization—from the microbial population level, where different genetic strains of a bacterial species, for example, fill different biological niches, say, within one layer of a human subgingival biofilm; to the microbial species level, where different bacterial species inhabit different layers of this biofilm; to the tissue level, where the makeup of a microbial community on the tongue is different from that lining the gums of the subgingival space; to the organ level, where the flora of the mouth is distinct from that on the skin; to the level of the organism as a whole. Individual organisms are, in turn, parts of communities that are arranged at progressively higher levels of organization, ultimately at the level of what we have traditionally referred to as an ecosystem, such as a temperate forest or a coastal marine wetland.

Until we begin to see ecosystems along such a continuum, we will fail to appreciate the vital and central role played by microbes in our lives and in the lives of all other species on Earth, both in health and in disease; we will pay insufficient attention to the enormous diversity and complexity of organization that exists at all the various sublevels of traditional ecosystems; and we will ultimately have a superficial and incomplete understanding of how ecosystems function to sustain the living world.

Provisioning Services

For millennia, people have harvested Nature's bounty for nourishment, shelter, and fuel. They have also used plant products to treat a range of illnesses, including malaria and other maladies. Many of the goods harvested from aquatic and land ecosystems are traded in economic markets. For example, at the beginning of the twenty-first century, the annual world fish catch from the oceans and from fresh water was about 130 million metric tons (about 143 million tons), valued in the range of 100 billion U.S. dollars.[2] Fish is a core component of peoples' diets in many parts of the world, such as in Africa and Asia, where some 20 percent of the population depends on fish as a primary source of protein.[3]

Land ecosystems, including grasslands and forests, are also important sources of marketable goods. Grasslands help supply people with a wide range of animal products, including meat, milk, wool, and leather. Forests supply people with many things, including food, timber, and wood for fuel. Fruits, nuts, mushrooms, honey, and many other foods are also extracted from forests. Wood, bamboo, grasses, and other plant materials are used to construct homes and other buildings. Organic material from trees and other plants supplies about 15 percent of the world's total energy consumption; in developing countries, it supplies almost 40 percent.[4,5] In addition, natural products extracted from many hundreds of forest and nonforest plants are used by industry. Examples include oils, resins, dyes, tannins, and insecticides.

Figure 3.2. Marsh Arab Reed House. This *mudhif*, a typical floating house of the Marsh Arabs of southern Iraq, is made from reeds tied and woven together, as it has been for thousands of years in this area. Saddam Hussein largely destroyed these marshes, but major international efforts are under way to help them recover. (From Nik Wheeler Photography.)

Regulating Services

CLEANING AIR

Both plants and soil microbes are involved in cleaning the air we breathe. Plant canopies, especially forest canopies, function as filters of particulates in the air and as chemical reaction sites that help regulate the composition of the atmosphere.[6] The major sources of atmospheric particulates are (1) the combustion of coal, gasoline, and fuel oil, (2) cement production, (3) lime kiln operation, (4) incineration, and (5) the burning of crops. These human activities produce fine particles less than 100 μm (micrometers) in diameter, such as black carbon, and coarse particulates (greater than 100 μm), such as dust. (A micrometer is one millionth of a meter, or approximately 0.00004 inches, so 100 μm is approximately 0.004 inches.) Plant canopies capture a variety of particulates, ranging from harmless sea salt aerosols near the oceans to dangerous lead particles alongside roads in countries, both industrialized and developing, where lead is still being used as a gasoline additive.

Plant surfaces, particularly moist leaf surfaces, are sites where a wide range of chemical reactions occur,

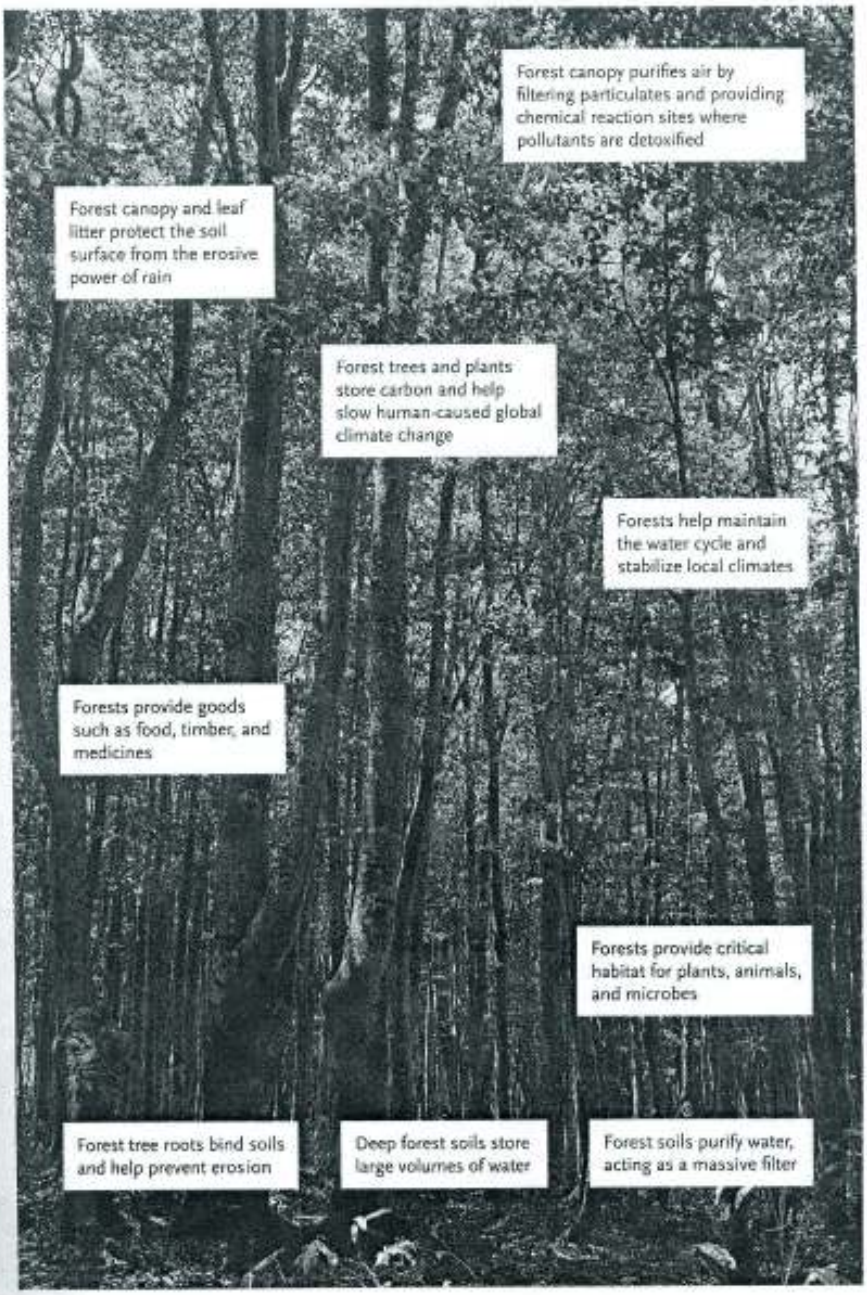


Figure 3.3. Temperate Forest Ecosystem Services (Original photo by Jin Young Lee, www.dreamstime.com. Text design by Tung Mei Chan.)

There, polluting compounds such as nitric oxide, the precursor of ground-level ozone, produced mainly by automobiles and power plants, can be transformed into harmless compounds.[7] Some soil microbes are also capable of many of these transformations. One group of microbes known as "methanotrophs," for example, that live in well-drained, well-aerated soils and belong to the Archaea (see chapter 1, page 11), break down methane,[8] a powerful greenhouse gas that is involved in global warming.

PURIFYING WATER

Many well-vegetated upland areas, freshwater wetlands, and estuaries function to purify water. The purification processes involved can be biological, physical/chemical, or a combination of the two.

Upland Areas

Forests, shrublands, and grasslands that occur in upland areas throughout the world are important sources of clean water for human use. The journey of water through these ecosystems is like slowly dripping water through a massive filter. The rain that falls on many of these ecosystems often contains substantial amounts of chemicals, such as inorganic nitrogen (in the form of ammonium or nitrate compounds), and other inorganic and organic compounds. As it percolates through the soil, the water is stripped of many of these chemicals, both by being taken up by plants and microbes and by coming into contact with chemically reactive sites on clay and on organic matter to which such compounds bind. For example, in healthy middle-aged forests in New England, rain enters with an average nitrogen load of about eight pounds per acre each year. Stream water leaving these forests often contains less than one-tenth the concentration of nitrogen that was present in the rainfall.[9]

Freshwater Wetlands

Since the dawn of civilization, freshwater wetlands have been absorbing and recycling nutrients from human settlements. This ecosystem service is performed by a variety of wetland ecosystem types, including those that occupy lowland areas along streams and rivers, and those that border lakes. As water flows through these wetlands, plants, microbes, and sediments filter out nutrients, such as nitrogen and phosphorus, from the water column. Plants take up these nutrients and incorporate them into root, stem, and leaf material. Microbes transform a water-soluble form of nitrogen into gaseous forms that are biologically inactive and harmless to the environment. And physical and chemical processes in sediments, such as those involving the adsorption (an accumulation of a substance on the surface of a solid, forming a molecular film) of phosphorus to particles, function to purify water.

Nutrient retention and processing, characteristic of natural wetlands, have been exploited in reconstructing former wetlands, such as is now occurring in the marshlands of southern Iraq,[10] or in the building of new ones, such as those being developed by some coastal cities and towns. They are constructed so that water flows slowly over sediments and through vegetation, giving them time to strip the water of

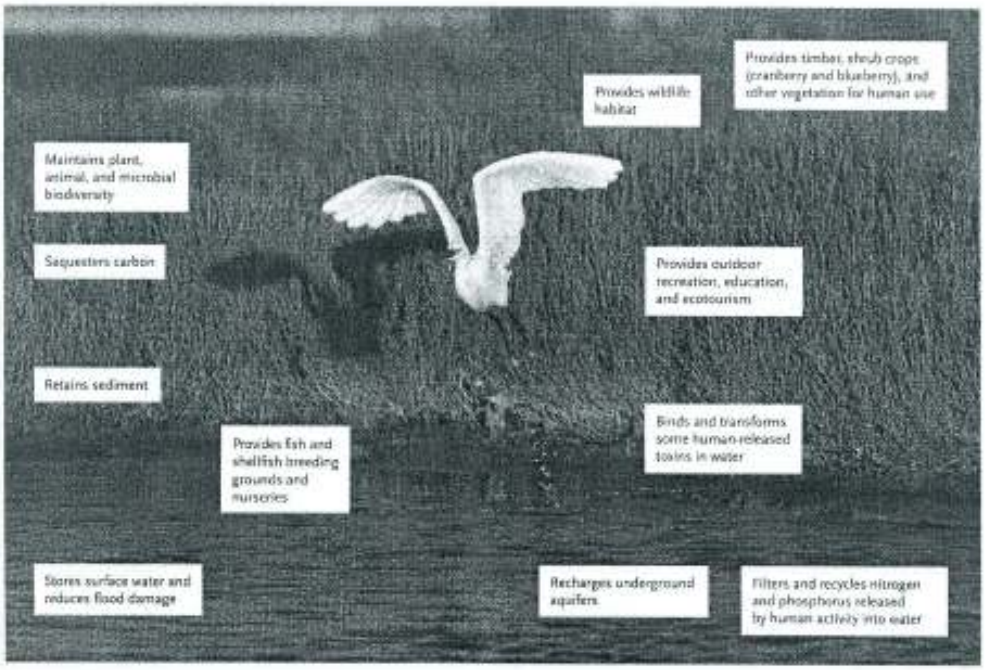


Figure 3.4. Freshwater Wetlands Ecosystem Services. (Original photo by Mauro Marini, www.dreamstime.com. Text design by Tong Mei Chan.)

nutrients.[11] In addition to controlling the rate of water flow, managers of constructed wetlands often keep vegetation in a rapid growth phase through periodic harvesting in an effort to maximize the amount and the speed of nutrient uptake. They also regulate oxygen levels in the sediments to increase the loss of gaseous nitrogen, and manipulate the supply of soluble iron and aluminum to enhance the rate of phosphorus removal.

Constructed wetlands also have the ability to remove human-made compounds, including some that are toxic, from flowing water. At a U.S. Environmental Protection Agency research laboratory in Athens, Georgia, for example, studies have shown that an enzyme produced by the invasive Parrot Feather (*Myriophyllum brasiliense*), a freshwater plant that can spread rapidly to clog rivers, ponds, and irrigation channels, effectively breaks down trinitrotoluene, better known as TNT.[12] This has led to several successful pilot projects in which constructed wetlands were able to remove the chemical from water that had been contaminated by military firing ranges. (See also "Binding and Detoxifying Pollutants in Soils, Sediments, and Water," below.)

Estuaries

Bivalve mollusks in estuaries, including mussels, clams, and oysters, act as filtering systems that can remove suspended materials and that consume algae secondary to

eutrophication (the overgrowth of algae in aquatic ecosystems resulting from excessive levels of human-released nutrients). An often-cited example is the filtering capacity of Eastern Oysters (*Crassostrea virginica*) in the Chesapeake Bay. For centuries, oysters in the bay were so numerous that they could filter its complete volume in approximately a three-day period. The result of this massive filtering activity was to maintain clear and oxygen-rich waters.

A combination of pollution, habitat destruction, overharvesting, and other pressures has dramatically reduced the oyster population of the Chesapeake Bay, and those of other major estuaries along the U.S. East Coast. For the Chesapeake, the decline has been so great that it now takes almost a year for the oysters to filter the bay, more than 100 times as long as it did as recently as about 100 years ago.[13] The result of this decline has been the loss of a critical ecosystem service, the filtering of water that has been essential to maintaining the quality of the bay. Its waters are now murkier and poorer in oxygen concentrations and in aquatic life.[14]

MITIGATING FLOODS

For millennia, many regions of the world have been subject to extreme weather events, including periods of excessively heavy rainfall and the short-term flooding of relatively flat areas, known as "flood plains," that border lakes, rivers, and streams. Flood plains include a variety of habitats such as forests and wetlands. Some flood plains bordering major rivers are vast, such as those of the Mississippi River, whose flood plain is up to 130 kilometers (80 miles) wide in some areas. Examples of other large river flood-plain ecosystems include the Sudd swamps on the White Nile in Sudan and the Okavango River wetlands in Botswana. Unaltered flood plains serve as habitat for many plant and animal species. For example, the Gran Pantanal of the Paraguay River in South America is home to an estimated 600 species of fish, 650 species if birds, and 80 species of mammals.[15]

Flood plains are one of Nature's "safety valves." Following excessive rains, floodwaters flow over riverbanks and into the forests, wetlands, and other habitats that constitute flood plain ecosystems. Some of the water is soaked up by the soil. In time, the floodwaters recede, leaving behind a new supply of nutrient-rich sediments that enhance the flood plain's fertility and make these ecosystems among the most productive in the world.

Many ancient civilizations—for example, in Mesopotamia, Egypt, China, and India—used flood plains as agricultural sites, taking advantage of the periodic enhancement of soil fertility by the flood-related deposition of nutrient-rich sediments. As human populations have grown, development pressures on flood plains in many parts of the world have increased, resulting in a compromising of the ability of flood plains to absorb floodwaters.

The Mississippi River and its tributaries, which drain about one-third of the lower forty-eight states, flooded during the summer of 1993 following above average rains in the first half of the year and an unusually high number of torrential rain events during the summer. Such extreme precipitation events, including both torrential rains and droughts, are predicted to increase in frequency and intensity as a result of global warming.[16] The loss of the flood plain alongside the river compounded

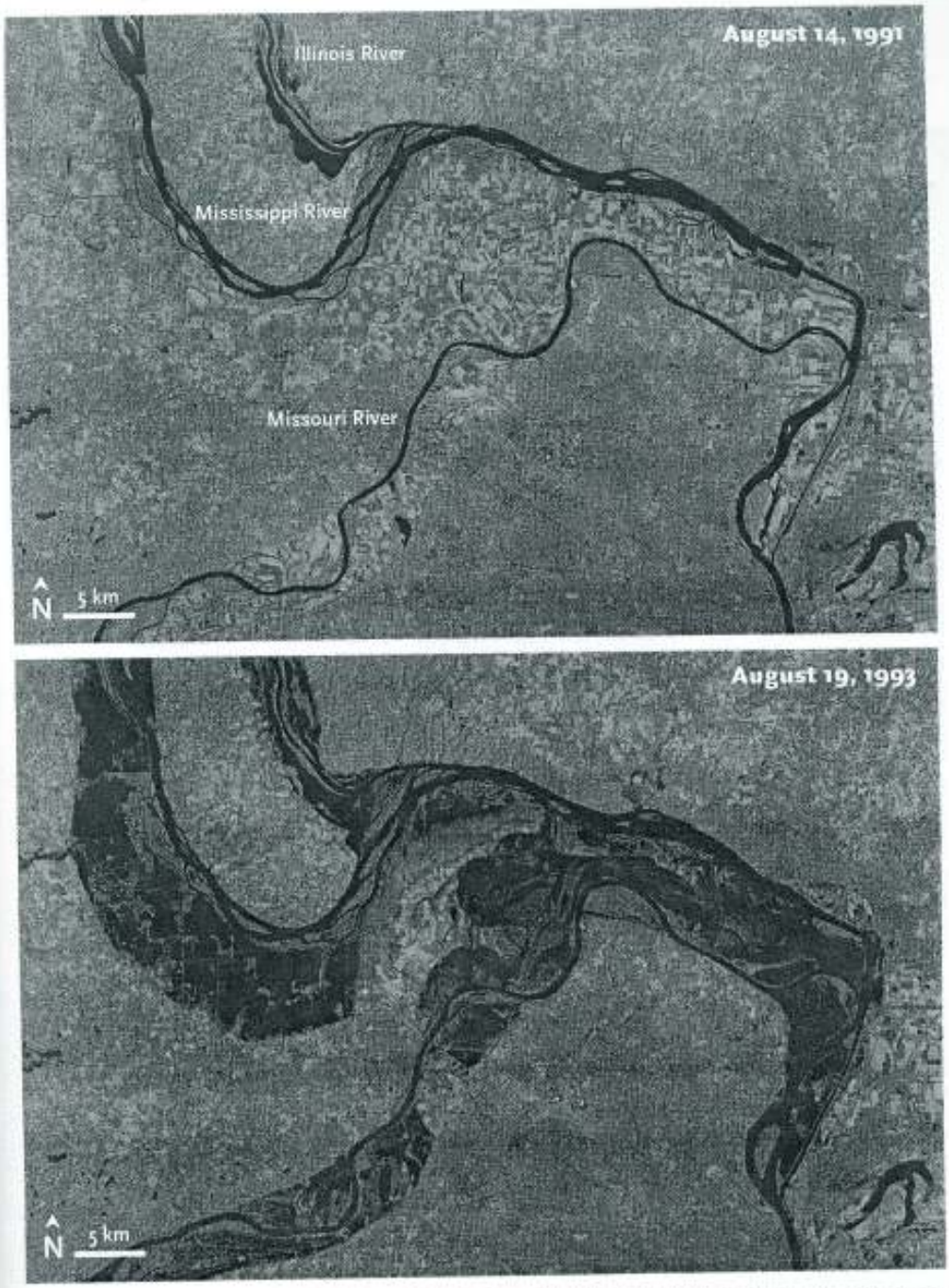


Figure 3.5. St. Louis, Missouri, Before and After the Summer Flooding of 1993. Satellite photos taken August 14, 1991, and August 19, 1993. The Illinois, Missouri, and Mississippi Rivers breached their banks secondary to torrential rains and to the compromising and development of the rivers' flood plains, flooding millions of acres of towns, cities, and farmland. (Courtesy of NASA Earth Observatory Photo.)

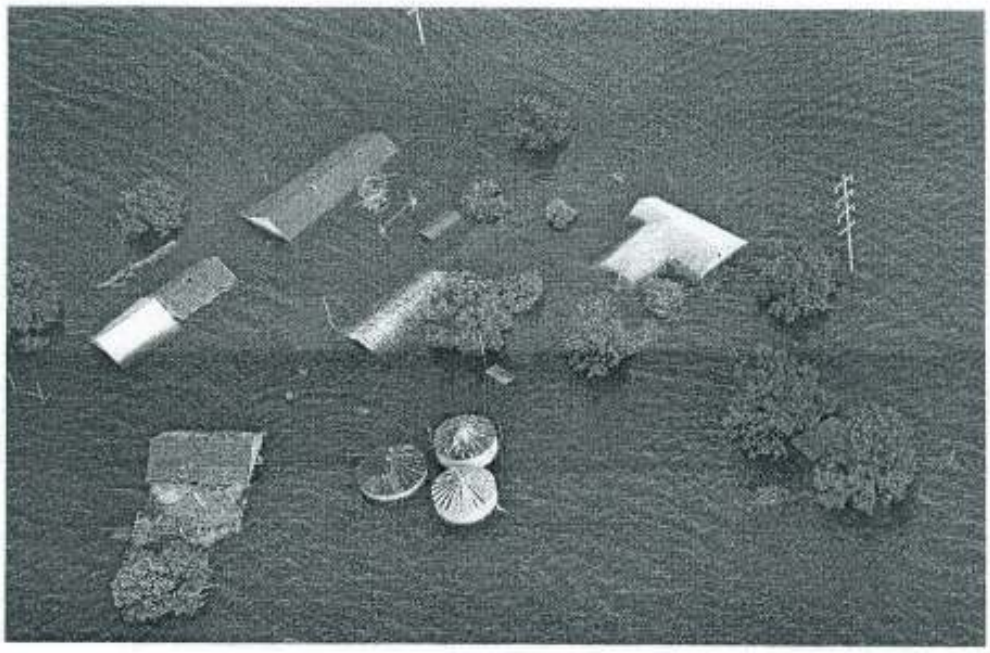


Figure 3.6. Flooded Farm near Hillview, Illinois, on the Illinois River, Summer 1993. (Courtesy of Jim Wark, Airphoto.)

the devastation. Floodwaters spread over 9.5 million hectares (23 million acres), inundating farms, towns, and cities in nine midwestern states—North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois. The toll was enormous—50 people were killed, more than 70,000 homes were lost, 8.7 million acres of farmland were damaged, and total property losses were estimated at $12 billion.[17]

The high cost of the flood damage has been attributed to three practices: the drainage of flood plain wetlands, the building of permanent structures on flood plains, and the construction of levees to keep floodwaters from spilling over. In the Midwest, one of the original, and most important, changes to the landscape was, in addition, the loss of beaver dams. Beavers had shaped the flood plain landscape for thousands of years prior to European settlement. The seventeenth- and eighteenth-century fur trade brought the beaver to the verge of extinction in Illinois by the mid-nineteenth century (the beaver is once again abundant there due to its reintroduction). With the loss of beaver dams, and the start of intensive farming that required the draining of wetlands, came unimpeded tributary flow into the Mississippi River and increased flooding.[18]

During the past century, the drainage of wetlands in the U.S. Midwest intensified to produce more farmland and home sites. The flood-moderating service of these wetlands was not recognized. Missouri, Illinois, and Iowa, the three states that suffered the most damage from the 1993 floods, have less than 15 percent of their original wetlands.[19]

Building permanent structures such as barns, houses, and factories on flood plains also increases damage and the accompanying financial losses when floods occur, for two reasons. First, they are valuable properties. Second, these structures and their associated roads, parking lots, and other paved surfaces reduce the area of soils and sediments that are able to absorb floodwaters. If forest or other natural vegetation covers a flood plain, the floodwaters spread over the land slowly, and the land absorbs much of the water. Because land in a developed flood plain is less able to absorb excess water, the water spreads more rapidly and extensively.

Finally, hundreds of levees were built along the Mississippi and its tributaries to hold floodwaters back from the flood plain. Although levees may save lives and property where they are built, they cause floodwaters upstream to surge, damaging farms and towns that are less protected. In addition, they prevent the periodic deposition of sediment in the flood plains that replenishes the soil, serving to maintain its levels and its ability to absorb floodwaters. The building of levees and the subsequent loss of marsh soils, along with the draining, destruction, and development of freshwater wetlands, is thought to be, in part, responsible for the massive flooding of areas of New Orleans following Hurricane Katrina.[20]

CONTROLLING EROSION

Inland Sites

Vegetation provides natural protection for soils against erosion in several ways. First, the plant canopies intercept rainfall and reduce the force with which rainwater hits the soil surface. Second, roots bind soil particles in place and prevent them from washing down slopes. Third, old root channels help to minimize the powerful force of surface runoff by routing water into the soil, like drain pipes. Animal burrows serve the same function.

The U.N. Food and Agriculture Organization (FAO) has estimated that during the closing decade of the twentieth century, erosion damaged or destroyed each year between ten and twenty million acres of the world's cropland. Erosion has affected some areas more than others. In China by 1978, erosion had forced the abandonment of about one-third of all arable land. Erosion rates in many parts of Africa are estimated to be nine times higher than erosion rates in Europe.[7]

Erosion can affect human health in both direct and indirect ways. By reducing the area of croplands, erosion may contribute to food shortages and compromised nutritional states among people in some developing countries. Erosion can also directly cause deaths through mudslides. For example, intense rains falling on steep slopes that were cleared of their forests in the Caribbean and throughout Central and South America have resulted in thousands of people dying in massive mudslides in recent decades, including those accompanying Hurricane Mitch in 1998.[21]

Large-scale mudslides became the signature of Hurricane Mitch, which grew to become the Atlantic basin's fourth strongest hurricane ever, with sustained winds of 180 mph for more than 24 hours. The hurricane stalled off the coast of Honduras from October 27, 1998, until the evening of October 29, dropping up to 25 inches of rain in

Figure 3.3. Mudslide in the Hamlet of Rincon Argentino, in Tecpan, Guatemala, October 5, 2005. This mudslide, a result of torrential rains from Hurricane Stan, killed four children and left fifteen people missing. Mudslides in places were a half a mile wide and 15 to 20 feet deep. (Courtesy of Reuters/Mario Linares.)

one six-hour period in some places. The heavy rains led to widespread flooding and mudslides that resulted in 33,000 homes being destroyed, at least 7,000 deaths and 5,000 missing, and thousands of cases of cholera, malaria, and dengue fever.[21]

Hurricane Stan, which dumped torrential rains on Guatemala and other parts of Central America from September 29 through October 5, 2005, killed more than 1,036 people in Guatemala alone; left 130,000 homeless and three million without power, water, and other basic services; destroyed crops and livestock; and damaged nearly 2,500 miles of roads, cutting off many regions from outside help.[22] A U.S. Geological Survey research team reported that many of the deadly mudslides occurred in areas where the forests had been cleared to make way for agriculture.

Ocean Edge

Mangrove forests and salt marshes are the most common ecosystems found in many coastal areas. They perform an important ecosystem service by buffering the land

BOX 3.2

The Tsunami of December 26, 2004

The great Southeast Asian Tsunami of December 26, 2004, which killed more than a quarter million people, left millions homeless, and caused widespread devastation in Indonesia, Thailand, India, Sri Lanka, and other countries, provides an important case study for the role that natural coastal ecosystems may play in the physical protection of people and land against storm surges. Preliminary studies in Sri Lanka suggested that in areas where coral reefs, vegetated coastal sand dunes, and healthy mangrove forests were intact, damage to the coastal zone was lessened. And investigations in Thailand, particularly in the most affected province of Phang Nga, demonstrated that mangrove forests and seagrass beds significantly mitigated the destructive force of the tsunami.[a-c] Model simulations have supported the role of coral reefs in buffering the impacts of tsunamis.[d] But some researchers have stated that while mangroves and coral reefs dampen the destructive action of normal storm-generated waves, their protective roles during tsunamis are less clear, and that distance from the epicenter, elevation and distance from the shore, shoreline profiles, wave characteristics, and other factors may be as or more important in determining levels of destruction on land.[e]

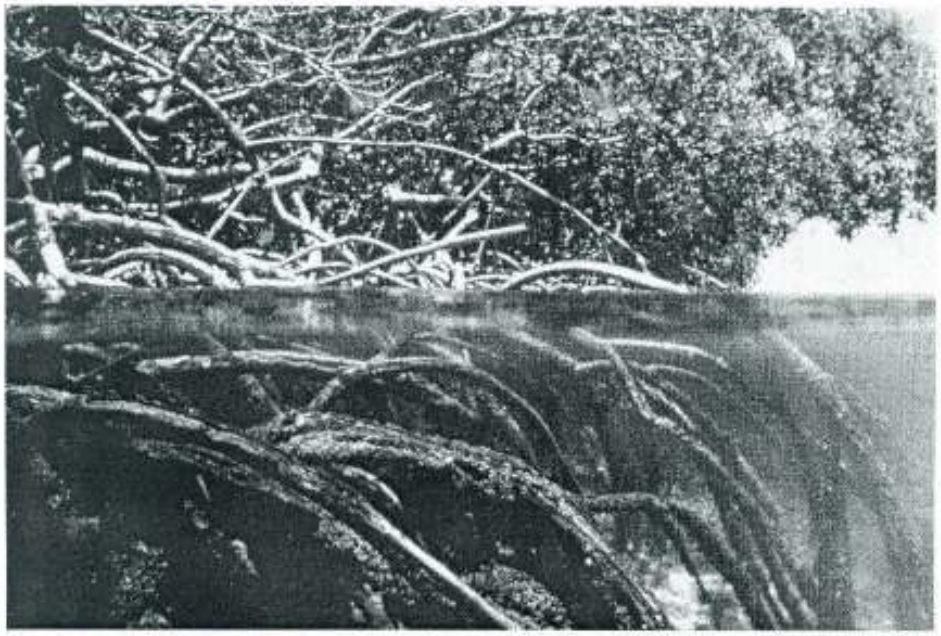


Figure 3.8. Photo of Mangroves in Southeast Florida. The strong, dense branches and roots of mangroves break up the force of waves and storm surges and stabilize coastlines. (Courtesy of U.S. National Oceanic and Atmospheric Administration.)

against ocean storm surges. Plants in these ecosystems stabilize submerged soil sediments, thereby preventing coastal erosion. Scientists at the Mangrove Ecosystems Research Centre in Hanoi, North Vietnam, for example, have compiled evidence that mangroves are more effective than concrete sea walls in controlling the raging floodwaters from tropical storms.[23] Forested areas can also help dampen the force of hurricanes and protect coastal communities, as was seen with Hurricane Felix and its 160-mile-per-hour winds that came ashore in northern Nicaragua and southern Honduras on September 4, 2007.

However, both salt marshes and mangrove forests are rapidly being destroyed. To uninformed people, salt marshes have often appeared to be worthless, empty stretches of land. As a result, many of them have been used as waste dumps or have been filled in with dredged sediments to form artificial land for building homes or industrial complexes. Mangroves are also under assault from other forms of coastal development, such as from shrimp aquaculture and unsustainable logging.[24] Some countries, such as the Philippines, Bangladesh, and Guinea-Bissau, have lost 50 percent or more of their mangrove swamps.[25] Losses of salt marshes and mangroves have consequences beyond the loss of ocean storm buffers. Most important, these land-margin ecosystems are among the most productive breeding grounds and nurseries for commercially important fish (see section on aquaculture in chapter 8, page 373) and are important habitats for many species of birds.

BINDING AND DETOXIFYING POLLUTANTS IN SOILS, SEDIMENTS, AND WATER

One of the consequences of our industrial and agricultural activities is that we have spread, both intentionally and unintentionally, heavy metals and radioactive elements worldwide, a result of having mined them for a variety of purposes. We have also released into the global environment, in varying concentrations, tens of thousands of man-made chemicals—pesticides, medicines, industrial chemicals, household products, and other compounds—some of which degrade very slowly, accumulate in the food chain, and eventually end up in our own tissues (see the section on pollution in chapter 2, page 51). In some places where they are deposited, they reach toxic levels that can render such areas unusable by humans and a danger to many other forms of life.

Scientists are using a variety of vascular plants that have the capacity to concentrate potentially toxic elements without doing themselves harm, to clean up and restore these contaminated areas. The India Mustard Plant (*Brassica juncea*), for example, can accumulate lead, chromium, cadmium, nickel, zinc, copper, and selenium; the Alpine Pennycress (*Thlaspi caerulescens*) binds zinc and cadmium; and the Common Sunflower (*Helianthus annuus*) can capture some radioactive substances.[27–28] These "abilities" are being put to use in what is called "bioremediation" or "phytoremediation." Such plants are particularly abundant in tropical or subtropical regions, perhaps because high metal concentrations in their tissues may confer some degree of protection against plant-eating insects and microbial pathogens that are common in these regions. Other species of plants are also being

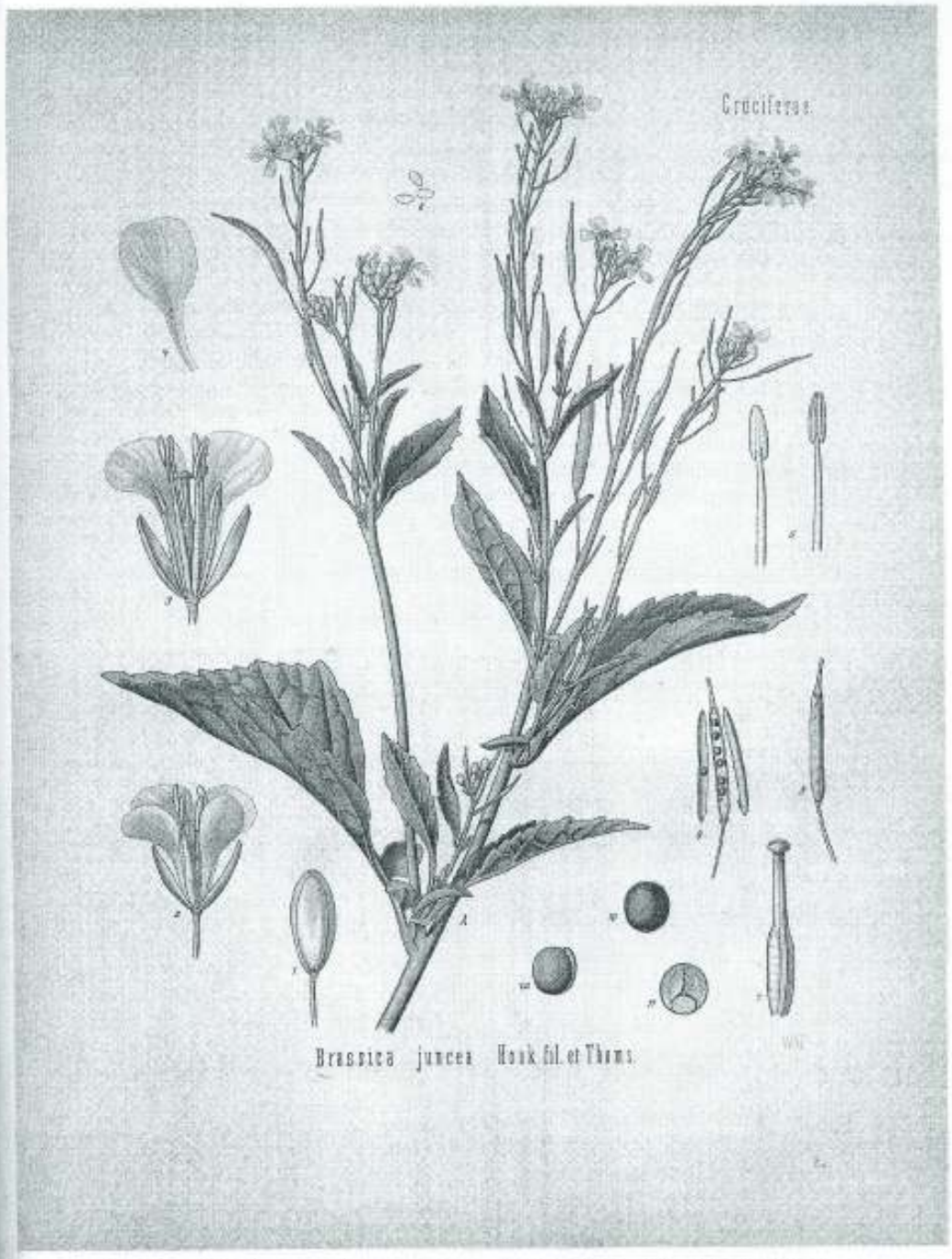


Figure 3.9. The India Mustard Plant (*Brassica juncea*). Brassica juncea can absorb in its tissues a variety of toxic metals. (© 1995–2004 Missouri Botanical Garden. From F.E. Kohler's *Medizinal-Pflanzen*, Gera-Untermhaus, 1887; www.illustratedgarden.org/mobot/rarebooks/)

investigated for their ability to bind toxic substances, including alfalfa, tomato and pumpkin vines, bamboo, Cordgrass, willow and poplar trees, and even the invasive Kudzu.[30] And some nonplant species, such as the lichen *Trapelia involuta*, which can concentrate uranium in its tissues,[31] and some fungi, such as "white rot fungi" (particularly *Phanerochaete chrysosporium*) and "brown rot fungi" (notably, species of *Gloeophyllum*), which are able to accumulate heavy metals,[32,33] are also being studied for their bioremediation potential.

Sometimes the presence of plants growing on contaminated sites signals their ability to accumulate toxic substances. Recently, Brake Ferns (*Pteris ensiformis*), common in southeastern parts of the United States and in some other parts of the world, were found growing at a central Florida lumberyard where soils were heavily polluted with arsenic from wood preservatives (e.g., those used in "pressure-treated wood"). The Brake Ferns were taking up the arsenic in their tissues. Another arsenic-binding plant, the invasive, aquatic Water Hyacinth (*Eichhornia crassipes*), has been used to remove arsenic from drinking water.[34] Arsenic-contaminated drinking water is a problem in many parts of the United States, especially in the West and in Alaska. It is also a significant problem in other parts of the world, such as Bangladesh, where more than 60 percent of the groundwater contains high concentrations. In Bangladesh, millions of people have been exposed to arsenic levels that increase their risk for acute toxic effects, such as vomiting, esophageal and abdominal pain, and bloody "rice water" diarrhea; and chronic effects, such as keratosis (a thickening of the skin), changes in skin pigmentation, and cancers of the skin, lungs, bladder, and kidney.[35]

Figure 3.10. Brake Fern (*Pteris ensiformis*). (Courtesy of National Parks Board, Singapore.)

Two phytoremediation examples stand out as models for environmental cleanup and public health protection. The first involves an experiment conducted in a small pond near the ill-fated Chernobyl nuclear power plant in the Ukraine. The pond, like other areas surrounding Chernobyl, was heavily contaminated with strontium-90, cesium-137, and other toxic radioactive substances that had been released during the reactor fire in 1986. Scientists grew Sunflowers (*Helianthus annuus*) on Styrofoam rafts floating in the pond, with their roots dangling in the water like those of lettuce plants growing in hydroponic tanks. The Sunflowers were found to rapidly accumulate radioactive strontium and cesium in their tissues to levels that were several thousand times higher than concentrations in the water.[36]

Another noteworthy success story was the cleanup of a lead-laced tract of land at the DaimlerChrysler company complex in Detroit. The cleanup process was straightforward. First, the top four feet of soil were moved to a nearby site and planted with India Mustard and Sunflowers, both of which can accumulate lead. The lead concentration in the soil was reduced by 43 percent as a result of these plantings, which brought the site into compliance with both federal and state regulations. The project cost about half of what it would have cost to cart the 5,700 cubic yards of soil to a hazardous waste landfill. Instead, the cleanup crew had to dispose of only a few cubic yards of lead-rich plant material.[37]

Some microorganisms in naturally functioning estuarine and marine ecosystems are also able to perform the ecosystem service of detoxifying wastes generated by humans, such as petroleum and petroleum byproducts, such as gasoline, that are spilled into these environments on a regular basis. Many of the component compounds present in these spills carry health risks for humans and for many other organisms. When these compounds adhere to sinking particles, they settle to bottom sediments, where in some settings, naturally occurring microbes, such as the marine bacterium *Alcanivorax borkumensis* SK2, are able to detoxify them, ultimately turning them into carbon dioxide and water.[38]

Microorganisms are also being investigated to turn other man-made chemicals into harmless substances. One, for example, an anaerobic bacterium named BAV1, has been found to break down vinyl chloride, a hazardous industrial chemical present in about one-third of all toxic waste Superfund sites in the United States.[39] Vinyl chloride can causes neurological symptoms such as dizziness and headaches with acute exposures, and a rare form of liver cancer with longer term exposures. Other microbes are able to degrade some pesticides, such as malathion, atrazine, and DDT, as well as such herbicides as 2,4,5 trichlorophenoxyacetic acid (commonly known as 2,4,5 T),[40-43] and to reduce the harmful effects of some radioactive elements.[44]

CONTROLLING PESTS AND DISEASE-CAUSING PATHOGENS

A pest is any organism that interferes in some way with human welfare. A variety of weeds, insects, rodents, bacteria, fungi, and other organisms compete with humans for food, affect fiber production, or spread disease. Croplands and pests go together. One estimate is that croplands support more than 50,000 species of plant pathogens, 9,000 of insects and mites, and 8,000 of weeds. The loss of productivity in these

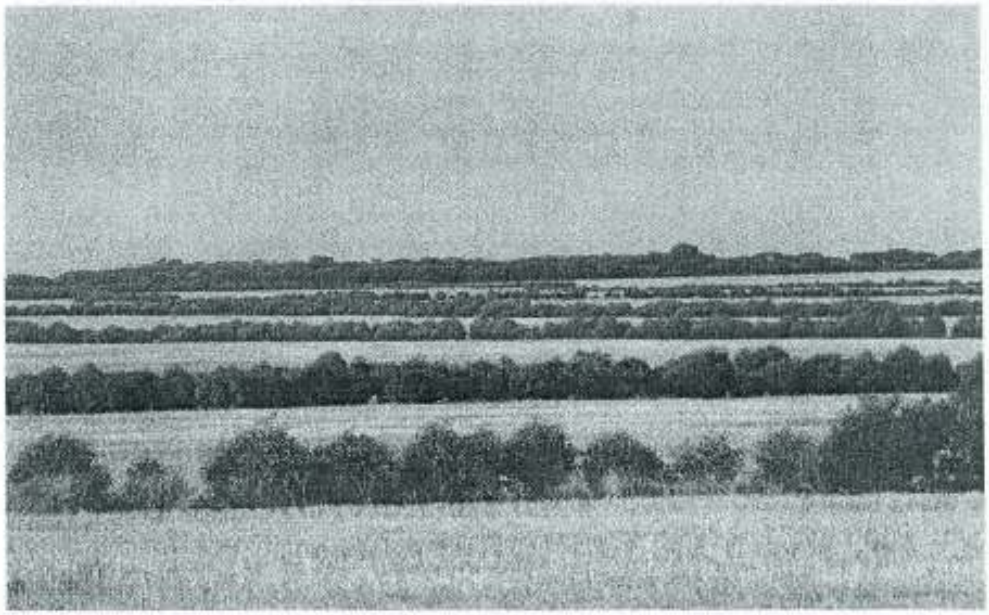


Figure 3.11. Eucalyptus Tree Hedgerows Separating Wheat Fields in Western Australia. (© Oil Mallee Company of Australia.)

managed ecosystems can be very high. Worldwide crop yields are reduced by about one-third by pests and disease.[45] And the losses could be much higher if it were not for ecosystem services that result in keeping populations of pests and disease-carrying organisms under control.

Sometimes we have to learn the value of natural controls the hard way. A story from China illustrates this point. In the 1950s, at the time of Mao Tse-Tung's Great Leap Forward, Chinese officials became concerned that flocks of birds were devouring large amounts of grain. To stop this attack on an already imperiled food supply, government officials declared that sparrows (which ultimately ended up meaning "any small perching bird") were "enemies" and therefore candidates for eradication. Millions of Chinese set about killing birds. Their success was frightening. Over several days in 1958, an estimated 800,000 birds were killed in Beijing alone. Major pest outbreaks resulted from this bird eradication program and led to significant crop losses. The mistake was ultimately realized and the bird killing was halted.[46]

Maintaining natural pest control sometimes requires understanding how landscape diversity relates to this critically important ecosystem service. Let us look at one example, that of hedgerows, which are linear stands of small trees or shrubs, natural or planted, that separate fields or pastures. In the southern German state of Bavaria, mosaics of such hedgerows and forest plantations border agricultural lands. They are modern Germany's most diverse woody habitats, with up to thirty species of woody plants and many species of herbivorous insects. The insects are for the most part specialists, and they feast on the woody plants in the hedgerow, while largely

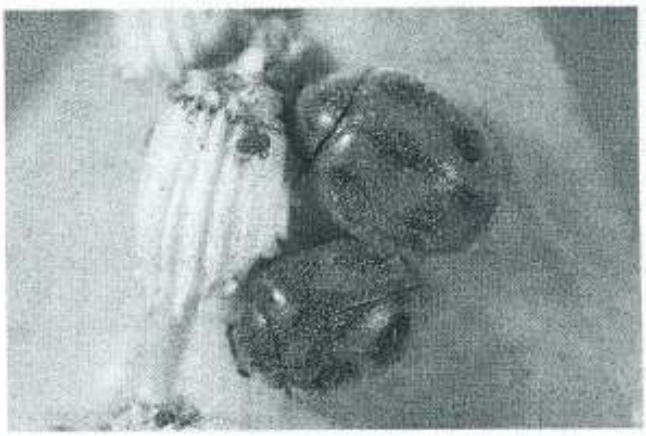


Figure 3.10. **Adult Vidalia Beetles (*Rodolia cardinalis*) Feeding on Cottony-Cushion Scale Insects.** Note the small reddish beetle larva on the back of the scale insect. (© Photo by Jack Kelly Clark, University of California Statewide IPM Project.)

ignoring the crops. The presence of the insects in the hedgerows attracts generalist predators and parasites, which feed not only on them, but also on aphids in the nearby grain fields. It is because of the hedgerows and their unique food webs that northeast Bavaria is one of the few places in Germany where farmers do not need to spray for wheat aphids. (See chapter 8 for more discussion of insects and other organisms that benefit crops.)

Using natural pest control as a model, scientists have tried to develop biological control mechanisms to replace pesticides. Biological controls involve the use of naturally occurring disease organisms, parasites, or predators to control pests. The use of a beetle to control Cottony-Cushion Scale (*Icerya purchasi*) is a good example. Cottony-Cushion Scale is a small insect that sucks the sap from the branches and bark of many fruit trees, including citrus trees. A native of Australia, it was accidentally introduced into the United States in the 1880s. An American entomologist figured out that another organism from Australia, the Vidalia Beetle (*Rodolia cardinalis*), was very effective in controlling scale. Because the beetle feeds exclusively and voraciously on the scale, its introduction almost eliminated Cottony-Cushion Scale in orchards within a few years. Today, both the scale and the beetle are present in very low numbers in U.S. orchards, and the scale is not considered an economically important pest.[17]

MODIFYING REGIONAL AND LOCAL CLIMATE

While climate plays a major role in the distribution of vegetation globally, vegetation also has a major influence on local and regional climates. For example, the rainfall in the Amazon Basin is, in part, a consequence of the existence of the region's forests. About half of the mean annual rainfall in the basin is recycled by the forests themselves via evapotranspiration—a process that accounts for the total amount of water transferred from plant-covered surfaces of Earth to the atmosphere, which

combines evaporation from open bodies of water and from the soil, with "transpiration," the movement of water within plants and its eventual loss to the atmosphere as water vapor. Computer modeling studies suggest that extensive deforestation in the Amazon could dramatically reduce rainfall in the region so that the forests might not be able to reestablish themselves. At the local scale, trees create "microclimates" by providing shade and surface cooling associated with evapotranspiration. Deforestation can also result in climatic change in areas adjacent to the forest, with losses in rainfall that can affect agriculture and the availability of water in these areas.[48-50]

Storing Carbon and Stabilizing the Climate

Land ecosystems of the world are large storehouses of organic carbon. Estimates place these carbon stores in the range of 2,100 billion metric tons, or BMTs (about 2,300 billion or 2.3 trillion tons). About 600 BMTs of this are stored in plant tissue, and 1,500 BMTs are stored in the soil as organic matter.[51] Recent analyses of the global carbon cycle indicate that carbon stores, in at least some land ecosystems, are growing, albeit in small annual increments. Furthermore, it is argued that this growth in plant and soil carbon stocks is slowing the buildup of carbon dioxide in the atmosphere, thereby slowing the rate of climate change and providing the valuable ecosystem service of stabilizing the global climate system.[52]

Over the past decade, environmental policy makers have recognized the important role that terrestrial carbon sinks play. In fact, as part of the U.N. Framework Convention on Climate Change, policy makers have sought to increase the size of these sinks through direct management actions as a way of slowing climate change. It is important to note that while terrestrial carbon sinks are enormously important over the near term in taking up our carbon dioxide emissions, we should not rely on them to bail us out over the long term. By the middle of the twenty-first century, they may be so reduced in size that their contributions in taking up carbon, relative to the amounts released from the burning of fossil fuels, may be minimal.

Cultural Services

RECREATION

Outdoor recreation contributes to human well-being around the globe in many different ways. Recreational opportunities on land include activities such as hiking, photography, camping, backpacking, large and small game hunting, bird watching, wildlife viewing, bicycling, and off-road vehicle use. Water-based recreational activities include fishing, boating, water skiing, and swimming. In the United States in 1995, almost 95 percent of the population sixteen or more years of age participated in some form of outdoor recreation.[53] In a recent poll in the United States, more than 65 percent reported that they use the outdoors for health and exercise, relaxation, and stress reduction.[54] Tourism, or as it is now called, "eco-tourism," centered on wildlife and nature reserves, is one of Africa's fastest growing industries, although it will be sustainable only when the needs of native communities are

BOX 5.3

So Intricately Is This World Resolved

So intricately is this world resolved
Of substance arched on thrust of circumstance,
The earth's organic meaning so involved
That none may break the pattern of his dance:
Lest, deviating, he confound the line
Of reason with the destiny of race,
And, altering the perilous design,
Bring ruin like a rain on time and space.

taken into account, and when a fair proportion of the profits received are used to benefit local populations.

PSYCHOLOGICAL, EMOTIONAL, SPIRITUAL, AND INTELLECTUAL VALUES

The value of leisure in natural settings to humans is multiple and includes (1) personal psychological benefits such as better mental health, personal development and growth, and personal appreciation; (2) psychophysiological benefits such as improved cardiovascular health; (3) social and cultural benefits, such as community satisfaction, reduced social alienation, tighter family bonding, a greater nurturance of others, increased cultural identity, and diminished social problems by at-risk youth; (4) economic benefits such as reduced health costs, increased productivity, less work absenteeism, and decreased job turnover; and (5) environmental benefits such as improved relationships with, and a greater understanding of, our dependency on the natural world. Edward O. Wilson's "biophilia" hypothesis suggests that many of these benefits may derive from our innate and hard-wired bond with other living organisms.[39]

Our natural world is a thing of beauty largely because of the diversity of living forms found in it. Artists have attempted to capture this beauty in drawings, paintings, sculpture, and photography, and it has inspired poets, writers, architects, and musicians to create works reflecting and celebrating the natural world. This work has led to fulfillment and rejuvenation for the artists and their audiences.

Nature also provides for many people great spiritual value. This is true not only for those who believe that all living things are God's creation and must be treated with everlasting reverence, but also for those who do not believe in God at all, but who nevertheless regard life, in all its beauty and variety and mystery, with a profound sense of awe and wonder. Life on Earth may be as sacred to many nonbelievers as it is to any deeply religious person who worships God.

Trying to understand the incredible complexity of biological systems and how organisms have evolved over more than 3.5 billion years is for some of us the most challenging, fascinating, and fulfilling way we could ever imagine to use our powers of observation and our intellects. It may also be the most important, because it will be through our own understanding of the natural world, and that by countless others, and through our collective efforts to help policy makers and the public understand its vulnerability to our nonsustainable behaviors, that we may have a chance to protect the global environment.

Supporting Services

PRIMARY PRODUCTION

Net primary production (NPP) is the amount of plant material generated during a year through the process of photosynthesis. It represents the energy base that powers all ecological processes and, as a result, underlies the capacity of ecosystems to provide all other ecosystem services.

For the world's land ecosystems, NPP is estimated to be about 120 billion metric tons (about 132 billion tons) of new organic matter each year in the form of plant leaves, stems, and roots. This material, in turn, functions as the material and energy base for all of the provisioning, regulating, and cultural services provided to humans by land ecosystems. The annual NPP of the oceans is similar in magnitude, and it supports services such as marine fisheries and the cycling of nutrients in the oceans.[39]

Scientists estimate that currently, human beings consume, degrade, or co-opt about 40 percent of all terrestrial NPP. This has major implications for other species and for ecosystems. For example, we are selectively harvesting plants to the point of causing local and regional extinctions, and we are clearing rainforests, altering the climate in those areas and reducing the viability of adjacent ecosystems.[57,58]

NUTRIENT CYCLING

The global cycles of carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur and perhaps as many as twenty-five other elements sustain life on Earth. As these elements move through the environment, either in organic or inorganic forms, they affect other basic ecosystem processes, such as photosynthesis and the decay of organic materials by microbes, and thus affect the way the world works in fundamental ways.

Human activities such as agricultural intensification, urbanization, industrialization, and the introduction and removal of species alter the flow of elements through the environment. These alterations contribute to major environmental

Table 3.1. Macronutrients and Micronutrients

Macronutrients	Micronutrients		
Carbon	Arsenic	Iodine	Tin
Hydrogen	Barium	Iron	Tungsten
Oxygen	Boron	Manganese	Vanadium
Nitrogen	Bromine	Molybdenum	Zinc
Phosphorus	Chlorine	Nickel	
Sulfur	Chromium	Selenium	
Calcium	Cobalt	Silicon	
Magnesium	Copper	Sodium	
Potassium	Fluorine	Strontium	

problems such as climate change, acid precipitation, photochemical smog, and "dead zones" in the oceans. We will need to better manage these element cycles if we are going to be successful in using the global environment in sustainable ways.

Table 3.1 lists the elements believed to be essential for animals, microbes, and plants. The elements required in large quantities are referred to as macronutrients. Six elements—carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur—are the major constituents of living tissue and comprise 95 percent of the biosphere.

POLLINATION AND SEED DISPERSAL

Pollination

Flowering plants and their animal pollinators work together in Nature. Because plants are rooted in the ground, they lack the mobility that animals have when mating. Many flowering plants rely on animals to help them mate. Bees, beetles, butterflies, moths, hummingbirds, bats, and other animals transport the male reproductive structures, called pollen, from one plant to another, in effect giving plants mobility. One of the rewards for pollinators is food—nectar (a sugary solution) and pollen. Plants often produce food that is precisely correct for a specific pollinator.[58] The nectar of flowers pollinated by bees, for example, usually contains between 30 and 55 percent sugar, the concentration that bees need in order to make honey. Bees will not visit flowers with lower sugar concentrations in their nectar. Bees also use pollen to make "bee bread," a nutritious mixture of nectar and pollen that is eaten by their larvae.[59]

Seed Dispersal

For millions of years, animals have consumed fruits and scattered piles of seed-rich dung across wide expanses of the landscape. This critical ecosystem service helped

the large-fruited trees to populate their habitats and migrate across the land in response to a variety of disturbances, including climate change.

As Yvonne Baskin notes, the distribution of plants in both temperate and tropical regions of the Americas may be quite different today from what it was during the Pleistocene epoch, tens of thousands of years ago, because of the demise of large fruit-eating animals that lived then. For example, the lowland forests of Central America lost mastodon-like gomphotheres, giant ground sloths, and other massive consumers of fruits, seeds, and foliage. Without these animals to disperse their seeds, fruit trees may have lost significant portions of their ranges over the millennia.[59] Two renowned botanists, Dan Janzen of the University of Pennsylvania and Paul Martin of the University of Arizona, have suggested that the same thing may have occurred when temperate North America lost its fruit-eating megafauna. Trees bearing large fruits such as the Osage Orange (*Maclura pomifera*), Pawpaw (*Asimina triloba*), and Persimmon (*Diospyros virginiana*) over the millennia grew progressively more sparse and limited in range.[61]

Today, toucans, agoutis, monkeys, fruit bats, and other frugivores (fruit eaters) and seed dispersers provide a critical ecosystem service that helps to maintain the biodiversity of terrestrial ecosystems and their essential life-giving services.

The Economic Value of Ecosystem Services

Numerous examples illustrate that ecosystem services have significant economic value. Here we consider three such examples, one that involves the delivery of clean water to New York City, and two others that involve the pollination of cash crops.

Clean Water for New York City

New York City has traditionally been known for its clean drinking water, which has been ranked as among the best in the United States. It originates in the watersheds of the Catskill Mountains. In recent years it has deteriorated in quality because of sewage and agricultural runoff that have overwhelmed the watersheds' natural purification systems. When the quality dropped below the standards of the U.S. Environmental Protection Agency, New York City's administration began to investigate the cost of replacing the natural system with an engineered filtration plant. Estimates for building the filtration plant ranged from six to eight billion U.S. dollars, with annual operating costs of around $300 million—a great deal of money to pay for what once cost nothing.[62]

These high capital and operating cost estimates prompted further thinking about the problem. The result of the reanalysis showed that it would be far cheaper (a one-time cost of $1 billion) to restore the integrity of the watershed's natural purification services, than to build the filtration plant. Faced with these alternatives, the city decided to restore the watershed. In 1997, it raised the necessary funds by issuing a

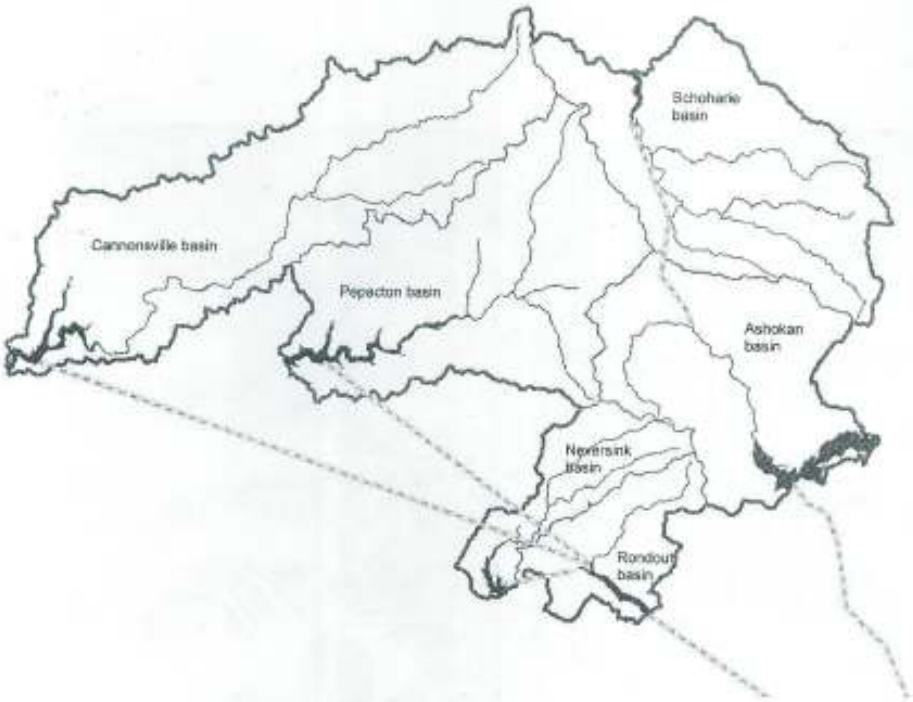


Figure 3.13. Map of the Catskill Watershed. The six major drainage basins are shown, along with their reservoirs and aqueducts en route to New York City. (Map created by the Catskill Center for Conservation and Development, December 2005. Data source: New York City Department of Environmental Protection, Bureau of Water Supply, Global Information Systems 2005.)

bond, both to purchase land in the watersheds of the Catskills and to halt its further development, compensating landowners for restrictions on private development, and subsidizing improvement of their septic systems.[43]

In this case, the citizens of New York City saved their clean water supply by preserving the natural watershed that created it, and saved billions of dollars in the process.[44] They also protected other valuable ecosystem services, such as the watershed's ability to provide flood control and to serve as a carbon sink to help mitigate global warming. Their success is serving as a model for other municipalities, such as Rio de Janeiro in Brazil.

Pollination of Cash Crops

COFFEE IN COSTA RICA

A good example of the economic value of the ecosystem service of pollination can be found on coffee farms of Central America. Working in Costa Rica, a team of World

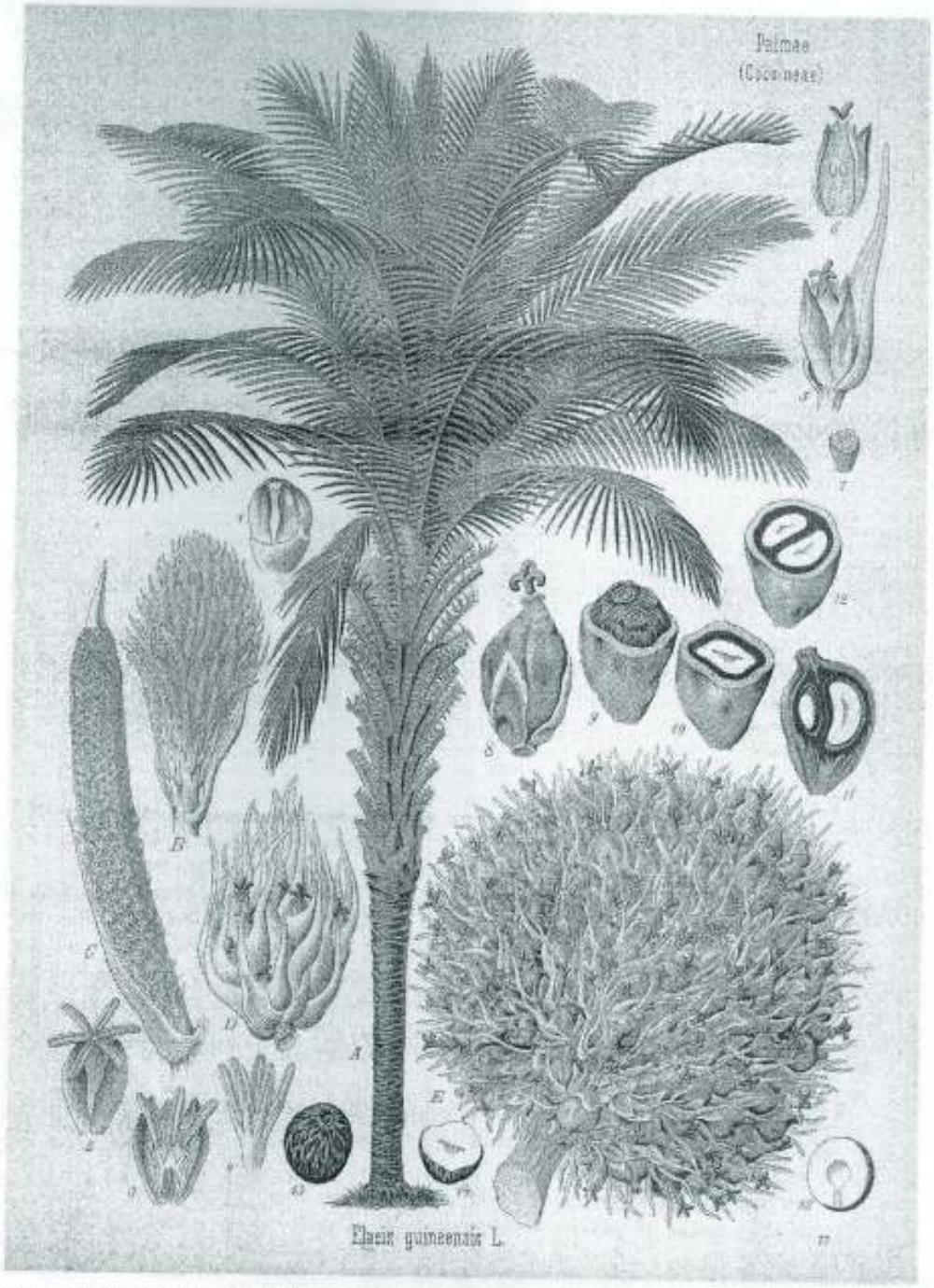


Figure 3.14. Oil Palm Tree (*Elaeis guineensis*). (© 1995–2005 Missouri Botanical Garden. From F.E. Kohler's *Medizinal-Pflanzen*, Gera-Untermhaus, 1887, www.illustratedgarden.org/mobot/rarebooks/.)

BOX 3-4

Palm Oil, Editors' Note

Millions of acres of Oil Palms have been planted in the tropics—in Asia, Africa, Latin America, and Oceania, and many millions more are being planned for the industrial production of palm oil. Palm oil is used in a wide range of foods, such as bread, margarine, cookies, and crackers (where it may be labeled only generically as "vegetable oil"), and in such products as lipstick, toothpaste, and soap.[1] As many as one in ten products on supermarket shelves contain palm oil. Demand is also rapidly growing for palm oil as a source for biodiesel fuel for electric power plants and vehicles, as substitutes for fossil fuels become increasingly attractive. While Oil Palms can be grown and harvested sustainably for local populations, as has been demonstrated in many parts of Africa and in some countries in South America, problems arise when its industrial-scale commercial cultivation requires massive deforestation.

Countries such as Malaysia are developing large-scale palm oil biodiesel production for export, mainly to the European Union, where interest in such biofuels is very high. The usual scenario is that rainforests are cut down and burned to make way for palm oil plantations (the severe forest fires in Indonesia in 1997, it should be noted, were triggered by such burning), threatening countless species because of deforestation.[2] Biodiversity is further eroded as a result of the high levels of chemical inputs—herbicides and fertilizers—that these palm tree monocultures require. Most disturbing is the deforestation that has been the consequence of new palm oil plantations in Indonesia and Malaysia, where 80 percent of the world's palm oil comes from, that is wiping out the rainforest homes of Orangutans (and other species) in these countries, 90 percent of which have already been destroyed. A recent report by the Center for Science in the Public Interest has concluded that palm oil plantations are the main threat to Orangutan survival on the island of Sumatra.[3]

A further problem with palm oil production in Southeast Asia comes from the draining and burning of large areas of peatland to establish new plantations, resulting in enormous, and previously uncounted, carbon emissions into the atmosphere.[4] A study by scientists from two Dutch organizations, Wetlands International and Delft Hydraulics, has concluded that the draining and burning of peatland in Indonesia for palm oil production currently releases more than two billion tons of carbon into the atmosphere each year, catapulting Indonesia into the position of the world's third leading producer of greenhouse gases.[5]

Deforestation in Malaysia, in part secondary to the proliferation of palm oil plantations, may also have played some role in the outbreak in Malaysia of Nipah virus disease in 1998, causing larger numbers of fruit bats carrying the disease to search for food, outside of the forests, in fruit trees bordering pig farms. With their excreta containing the virus, the bats were able to infect the pigs, which then passed the virus onto people. Such widespread deforestation can also result in the emergence and spread of other vector-borne infectious diseases carried by mosquitoes and snails (see chapter 7, page 294).

The interest in palm oil, and in some other tropical oils such as coconut oil, has been fueled in part by concerns about the use of *trans*-fatty acids, which can raise cholesterol, in food, and the belief that palm oil would not have such effects. But several studies have contradicted this belief, showing that palm oil raises cholesterol levels and promotes heart disease.[7-1]. Palm oil production may therefore be as unhealthy for human beings as it seems to be in some parts of the world for the environment.

Wildlife Fund researchers found that preserving forest fragments around coffee farms boosted their crop yields and raised average incomes by about $62,000 per year, roughly 7 percent of the average farm's annual income. The preserved forest provided a reliable source of bees to help pollinate the plants. Coffee-plant flowers near the forested areas received twice the number of bee visits and double the amount of pollen transfer compared to flowers farther away. The increased pollination led to 20 percent greater yields and 27 percent fewer deformed coffee beans.[8,9,10]

BOX 3.3

Assigning Dollar Values to Ecosystem Services, Editors' Note

There are large incentives for assigning dollar figures to ecosystem services, the most important of which are to help people recognize the value of what is being threatened by providing them with monetary equivalents, and to assist policy makers in how best to allocate often sparse public funds to help protect and restore natural environments. Many scientists and economists are involved in this work,[46] and clearly, there is a need for such calculations, because trade-offs generally must be made in public policy decisions. But while this may make sense for some services on local and regional scales, where the choices are clear and relatively easily monetized, such as with New York City's water supply or with the cash crops mentioned above, in the view of some scientists, it does not make sense in many, and perhaps in most, other cases.[48] By assigning a dollar value to an ecosystem service, there is the implication that we could re-create that service if we spent the amount of money designated. But this is not possible for services that are on so vast a scale that there is no way we could re-create them or are so complex that we barely understand how they work, such as the breakdown of organic matter and the recycling of nutrients or the sequestration of carbon by plants on land and in the oceans that helps regulate global climate. Is it possible to assign dollar values to services that are, in essence, priceless and that we cannot live without? The conclusion of the researchers who studied the disastrous results of the experiment known as "Biosphere II," where ecosystems were artificially created (at enormous expense and with significant scientific input) within a sealed environment in the Arizona desert in an effort to provide all the life support services necessary to keep four men and four women alive in that environment for a period of two years, was that, as no one yet knows how to re-create the natural biological systems that provide life support services in a "Biosphere II," we had better do everything in our power to preserve "Biosphere I"—Earth.*

PALM OIL IN MALAYSIA

Often a pollinator's worth to a crop is apparent only when it is missing or added. The story of Oil Palms in Malaysia illustrates this point. The African Oil Palm (*Elaeis guineensis*) was introduced to Malaysia from the forests of Cameroon in West Africa in 1917. At that time, the weevil that pollinated the palm was not brought along with the trees. For decades, the palm growers of Malaysia relied on expensive, labor-intensive hand pollination, much like the apple growers of Maoxian County in Nepal, as illustrated in the opening figure for this chapter. In 1980, the weevil was imported to Malaysia. The presence of this natural pollinator soon boosted fruit yield in the palms by 40 to 60 percent, and also generated substantial savings in labor, amounting to approximately $140 million per year.[47]

Threats to Ecosystem Services

A variety of factors affect ecosystem services. In this section, we review some of the major ones: climate change, deforestation, desertification, urbanization, wetland drainage, pollution, dams and diversions, and invasive species.

Climate Change

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (or IPCC) projects that human-induced climate change will lead to a warming of the surface of Earth on average of between 1.1 and 6.4 degrees Celsius (around 2 to 7 degrees Fahrenheit) by 2100.[18] The report also indicates that climate change will result in the disappearance or fragmentation of some natural ecosystems in particular areas. The ecosystem services that are expected to be lost are likely to be costly or impossible to replace.[19]

Climate change will affect terrestrial, freshwater, and marine ecosystems. When models that project future climates are coupled with those that project the future distribution of Earth's major terrestrial vegetation types, some dramatic changes show up in the simulations. For example, a recent simulation developed by the Hadley Centre of the U.K. Meteorological Office, using a highly regarded model that couples climate with terrestrial ecosystems, projects that climate change over the twenty-first century will result in the disappearance of much of the Amazon rainforest due to hotter and dryer conditions, and in its replacement by tropical savanna, a tree–grass mix similar to what exists today along the southern and southeastern edges of the Amazon Basin.[20] The loss of the rainforest will diminish the ability of the region to supply forest products, including timber, food (fruits and nuts), and medicines extracted from plants, animals, and microbes. In addition, the disappearance of rainforests will reduce the region's capacity to store carbon and will, in fact, result in the release of a large amount of carbon to the atmosphere that had been stored in organic forms in the forests' trees and soils. The newly released carbon will result in further warming and so is considered a positive feedback to the climate system, with further warming promoting more carbon release, leading to more warming, and so on. And the loss of the rainforests will affect local and regional climate, resulting in drier conditions.

Climate change will also have major effects on freshwater ecosystems and the services they deliver in some parts of the world, with probable changes in the amount, timing, and distribution of rain, snowfall, and runoff, leading to changes in water availability. An interesting example is related to the effects of climate change on snowpacks. Snowpacks serve as natural water storage in mountainous regions and poleward portions of the globe, releasing their water in spring and summer. Snowpacks will likely decrease as the climate warms, despite increasing precipitation, because scientists predict that more precipitation will fall as rain and that snowpacks will develop later and melt earlier. As a result, peak stream flows will very likely come earlier in the spring, and summer flows will be reduced, at times dramatically. Potential impacts of these changes include the increased possibility of flooding in

winter and early spring, and more water shortages in summer.[29] In regions where summer flows are dramatically reduced, and where competition for water resources is high, the in-stream ecosystem services, such as providing habitat for fish, will be disrupted and, in extreme cases, lost.

Unique marine ecosystems such as coral reefs will also be adversely affected by climate change, because they do not do well outside of a relatively narrow temperature envelope. The last few years have seen unprecedented declines in the health of coral reefs. During the 1998 El Niño, there were record sea-surface temperatures and associated coral bleaching (resulting from loss of the algae that live within the corals and that are required by them for survival). Up to 70 percent of the coral may have died in a single season in some regions (see chapter 2, page 35).[30]

When we lose corals, we also lose important ecosystem services. Coral reefs provide important habitat for fishes, render protection for coastal areas against storm surges, and are important recreation sites for tourists. Reefs are also one of the largest global storehouses of marine biodiversity, with untapped genetic resources.

Deforestation

The most serious problem facing the world's forests is deforestation. When forests are destroyed, they no longer provide us with ecosystem goods and services, and in the tropics, their destruction threatens the cultural and physical survival of native peoples. Deforestation often results in decreased soil fertility and increased soil erosion, with critical plant nutrients, such as nitrogen, being flushed from soils into streams in deforested watersheds.[31] Uncontrolled soil erosion, particularly on steep slopes, can affect the production of hydroelectric power as silt builds up behind dams. Soil erosion can also result in increased sedimentation of waterways, harming downstream fisheries. In drier areas, deforestation contributes to the formation of deserts through the process of desertification (see below). When a forest is removed, the total amount of surface water that flows into rivers and streams actually increases. However, because this water flow is no longer regulated by the forest, the affected region experiences alternating periods of floods and droughts.

Deforestation is a major factor in species loss. Many tropical species, in particular, have limited ranges within forests, making them especially vulnerable to habitat modification and destruction. Migratory species, as well, including birds and butterflies, suffer significant losses.

Deforestation leads to changes in both regional and global climate. Trees pump out substantial amounts of water into the air, which falls back to Earth as precipitation. When a large forest is cleared, rainfall may decline and droughts may become more frequent in the region. Tropical deforestation may also contribute to global warming by causing the release of stored carbon into the atmosphere as carbon dioxide.

Calculating the current rate of deforestation is beset by a number of difficulties, including a lack of adequate satellite coverage, disagreements over definitions, and other problems (see also chapter 2, page 30). For the period 1980–1995, the FAO estimates that forested areas in the industrialized world increased by about 2.7 percent, while they decreased by 10 percent in developing countries. As discussed in chapter 2, estimates of deforestation for tropical humid forests are around 120,000 square

kilometers per year (about 46,300 square miles), and for tropical dry forests, around 40,000 square kilometers per year (about 15,400 square miles).[71]

Desertification

Desertification, the degradation of once-fertile arid and semiarid land into nonproductive desert, involves the loss of biological or economic productivity and complexity in croplands, pastures, and woodlands. It is due mainly to climate variability and unsustainable human activities, the most common of which are overcultivation, overgrazing, deforestation, and poor irrigation practices.[72] Seventy percent of the world's drylands (excluding the hyperarid deserts), or about 3.6 billion hectares (about 8.9 billion acres), is degraded. While drought is often associated with land degradation, it is a natural phenomenon that occurs when rainfall is significantly below normal recorded levels for a long period of time.[73]

By definition, drylands have limited freshwater supplies, but precipitation can vary greatly during the year in these regions. In addition to this seasonal variability, wide fluctuations occur over years and decades, frequently leading to drought. Over the ages, dryland ecosystems have become attuned to this variability in moisture levels, with plants, animals, and microbes able to respond quickly to its presence or its absence. For example, satellite imagery has shown that the vegetation boundary south of the Sahara can move by up to 200 kilometers (about 124 miles) when a wet year is followed by a dry one, and vice versa.[73]

People have survived in dryland areas by adjusting to these natural fluctuations in climate. The biological and economic resources of drylands—notably soil quality, freshwater supplies, vegetation, and crops—are easily damaged. People have learned to protect these resources with age-old strategies, such as by adopting nomadic lifestyles in agricultural practices and in the raising of livestock. However, in recent decades these strategies have become less practical with changing economic and political circumstances, population growth, and a trend toward more settled communities. When land managers cannot, or do not, respond flexibly to climate variations, desertification is the result.

Desertification causes a reduction in a variety of ecosystem goods and services. Food production is undermined. If desertification is not stopped in an area, malnutrition, starvation, and ultimately famine may result. Famine typically occurs in areas that also suffer from poverty, civil unrest, or war. Desertification often helps to trigger a crisis, which is then made worse by poor food distribution and an inability of people to buy what is available. This is particularly true in Africa, where two-thirds of the continent is desert or drylands, and almost three-quarters of the extensive agricultural drylands are degraded to some degree.[74]

The stabilization of soil against water and wind erosion is diminished during desertification. Degraded land may cause downstream flooding, reduced water quality, sedimentation in rivers and lakes, and the silting of reservoirs and navigation channels. It can also cause dust storms that can exacerbate human health problems, including eye infections, respiratory illnesses, and allergies, and that can carry dust and its constituent organisms for thousands of miles (see "Introduced Species," chapter 2, page 47).

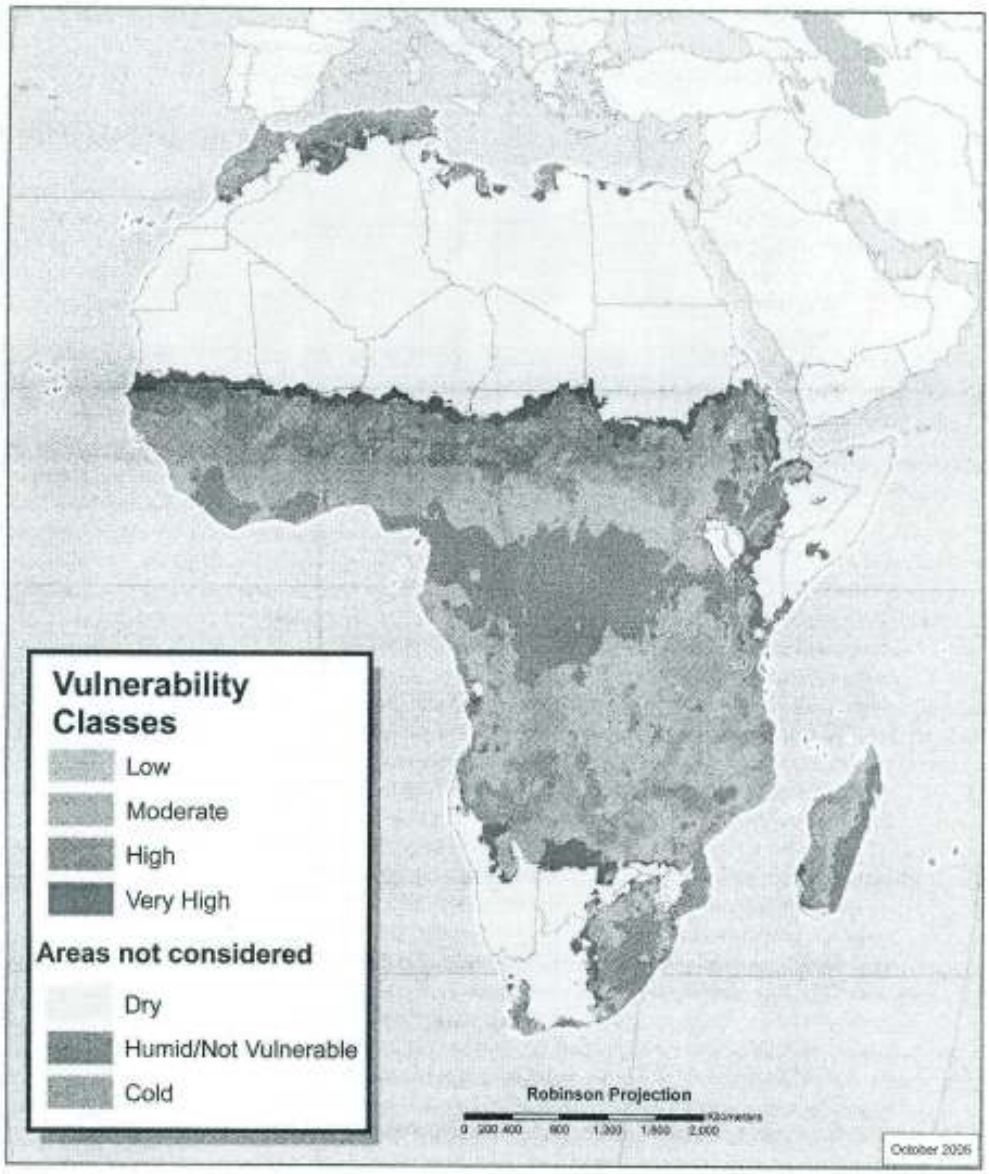


Figure 3.15. Desertification Vulnerability in Africa, 2005. (Courtesy of Soil Survey Division, Natural Resources Conservation Service, U.S. Department of Agriculture.)

TABLE 3.2. PERCENTAGE OF TOTAL POPULATION LIVING IN CITIES, BY COUNTRY/REGION

REGION	1950	1970	1990	2010
United States	64	70	75	82
Japan	35	53	63	66
Europe	51	63	72	74
Central America and the Caribbean	38	52	64	70
Sub-Saharan Africa	12	19	28	40
China	12	17	27	45
World	29	36	43	51

SOURCE: World Resources Institute, EarthTrends, 2006, available from earthtrends.wri.org/ [cited September 26, 2006].

Finally, critical habitat for both plant and animal species is lost as desertification proceeds. Loss of habitat has a range of consequences, including some economic ones. For example, in Africa, where desertification is currently having its greatest impact, ecotourism is being negatively affected in some areas.

Urbanization

Urbanization and population growth have been among the most unique features of the twentieth century. In 1700, only five cities in the world, all political capitals, were home to more than half a million people. By 1900, this number had climbed to forty-three cities. In 1950, only one city, New York, had more than ten million people. By 1975, there were five cities with populations of more than ten million, and in 2001, there were seventeen, with projections that this number will climb to twenty-one by the year 2015. By the year 2000, almost 50 percent of the world's people were urban dwellers.[10]

Cities can have significant benefits for the environment. They can attract people from rural areas where they may be doing more damage. Costa Rica, for example, is a conservation success story, as much because the Intel Corporation created thousands of jobs in San Jose as it is because land has been set aside in reserves. However, cities also gobble up land and take in ever increasing amounts of energy, water, and materials. They pump out commercial goods and services, along with pollutants and solid wastes. The impact of cities on the environment is wide ranging. Land-use changes and pollution associated with urbanization alter the goods and services that natural ecosystems provide. Plant and animal habitat is lost and some of ecosystems' stabilization functions are diminished. For example, urbanization often leads to increased erosion and reduced natural watershed control of floods. The filling in of wetlands for urban expansion eliminates their water cleansing function.[11] Many of these "lost" functions are costly, if not impossible, to replace.

Wetland Drainage

For hundreds of years in many places across the globe—for example, in the Netherlands, England, Germany, India, Burma, Vietnam, Thailand, the Philippines, Sudan, New Zealand, and the United States—people have drained wetlands to make new agricultural land. One estimate is that for the world as a whole, 10 million square kilometers (about 3.9 million square miles) of wetlands, an area about the size of Canada, have been drained during the twentieth century.[79]

In the lower forty-eight U.S. states, drainage has reduced the wetland area by about half—from 100 million hectares (about 247 million acres) to 53 million hectares (about 131 million acres). Much of the corn belt in the United States was created by the drainage of 17 million hectares (about 42 million acres), mostly in the twentieth century. In the South, the Mississippi River bottomlands were drained and eventually became important sites for growing rice and soybeans. In the Florida Everglades, another million hectares or so (about 2.5 million acres) were drained for agricultural use. And much of the Central Valley of California was also converted from wetlands to croplands and pastures.[79,80]

Wetland drainage has produced some of the world's most productive agricultural land, but at the expense of critical wildlife habitat, flood plains, and vitally important natural filtration systems for flowing waters.

Pollution

The pollution of rain and snowfall, air, water, and the land has diminished ecosystem goods and services in a variety of ways. The air pollutant ozone, for example, can reduce the growth of agricultural crops and plants of many different kinds in natural ecosystems. It is estimated that ground-level ozone levels in China are high enough to reduce crop yields nationwide by between 10 and 20 percent each year.[81] (The reader should note that ozone at ground level is a pollutant, damaging some plants, including crops, and causing flares of respiratory disease in people, while the same compound, O_3, in the stratosphere acts as a protective barrier, blocking harmful ultraviolet radiation from reaching the surface of Earth [see chapter 2, page 60].)

Pollution of rain and snowfall with sulfur and nitrogen compounds results in acid rain that damages plants and impoverishes soils. It also acidifies surface waters, killing plants and the animals that inhabit them. The nitrogen component of acid rain can act as a fertilizer to both land and water plants. In some estuaries, such as the Chesapeake Bay, the nitrogen inputs in acid rain are high enough to cause unwanted algal blooms that make the water unattractive for recreation and can lead to the creation of oxygen deficits in the water column associated with the decomposition of dead algae.[82] If the oxygen deficit is large enough, dramatic fish kills can result. Similar results can be caused by nitrogen pollution of estuaries from agricultural runoff and from point sources such as industrial complexes and sewage treatment plants.

Heavy metals spewing from smelters in such places as Sudbury, Ontario, have accumulated in soils downwind, causing the death of much of the plant life in the affected areas. Without the protection of vegetation cover, erosion has become a major problem at these sites.[83]

Dams and Water Diversions

Dams and water diversions have had major effects on the ability of aquatic ecosystems to provide goods and services. Dams have been built for several purposes, including extending irrigation, controlling floods, and generating electricity.

For dams, a slate of successes in food and energy production, and in flood control, has sometimes been overshadowed by environmental problems. One problem has been that dams change the natural flows of rivers and alter the quality of the aquatic habitat, resulting in species losses. A dam causes water to back up, flooding large areas of land and forming a reservoir, which destroys former plant and animal habitats. The natural beauty of the countryside is often negatively affected, and certain forms of wilderness recreation are compromised or made impossible.

In arid regions, the creation of reservoirs behind dams results in a greater evaporation of water, because the reservoirs have a larger surface area in contact with air than did the original rivers. As a result, serious water loss and increased salinity of the remaining water can occur. When the dammed water is used for irrigation in arid regions, there is always the risk of salinization, the process of various mineral salts accumulating in the soil. In rain-fed agriculture, precipitation that moves through the soil profile runs off to a river, carrying the salts away. Irrigation water, however, generally soaks into soils and does not run off the land into rivers. When the irrigation water evaporates, the salts remains behind and gradually accumulate. Salinization results in crop yield declines and, in extreme cases, renders the soil completely unfit for agriculture. This has occurred in some regions of the Central Valley of California, for example, once promoted as the "Fruit Basket of the World," where selenium salts have now reached high levels in irrigated agricultural soils.[84] By the end of the twentieth century, salinization had affected about 20 percent of the world's irrigated land.[85]

Dams may also encourage the spread of waterborne diseases, such as schistosomiasis, that may spread throughout local populations. Schistosomiasis is a tropical disease caused by a parasitic worm that can damage the liver, urinary tract, nervous system, and lungs. (See chapter 7, page 297, for a detailed discussion of schistosomiasis.)

Invasive Species

Centuries of human commerce and travel have led to a redistribution of Earth's biota. This process has accelerated through time, and today, invasive species are considered a major environmental issue. Invasive species

compete with native species for food and habitat or may prey on them. They may also cause disease. By altering the food web and affecting ecosystem functions in a variety of ways, invasive species reduce the ability of ecosystems to deliver life-sustaining goods and services to people.

While invasive species are occasionally introduced into an area by natural means, people are usually responsible for the introductions, both with and without intent. For example, because it had attractive flowers, the Water Hyacinth was brought from South America to Florida. Over the years, this rapidly growing plant has crowded out native species and impeded boat traffic, clogging many of Florida's waterways. In 1990, the Amazonian Water Hyacinth population also exploded in Lake Victoria in East Africa. Bordered by Kenya, Uganda, and Tanzania, Lake Victoria is an essential source of water and fish protein for its surrounding human populations. A combination of invasive species and nutrient enrichment from land-use changes have transformed it from a clear, well-oxygenated lake with an incredible diversity of cichlid fishes (a large family of freshwater fish, some species of which are important food fish, e.g., tilapia, that live mostly in tropical areas of Africa and the Americas) to a murky, oxygen-depleted, weed-choked lake with markedly reduced fish diversity. For many experts, the changes due to eutrophication and invasive species have been so great that the ability of the lake to meet human needs is now threatened.[86]

Conclusion

All of us, regardless of where we live on this planet, depend completely on its ecosystems and on the services they provide, such as food, water, climate regulation, disease management, the breakdown of wastes and the recycling of nutrients, spiritual fulfillment, and aesthetic enjoyment. A central conclusion of the Millennium Ecosystem Assessment, a recent report by the United Nations of the status of Earth's ecosystems and the services they provide to us, is that over the past half century, humans have changed our planet's ecosystems more rapidly and extensively than in any comparable period of time in our history. Most of these changes were made to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel. While the changes have clearly contributed to substantial gains in human well-being and economic development for some, many others have benefited little. In addition, the changes have resulted in a substantial and largely irreversible loss in the diversity of life on Earth and have had large costs in the form of the degradation of many ecosystem services and of an exacerbation of poverty for some groups of people. It is imperative that we understand much better than we do the makeup and functioning of the planet's ecosystems and how human activity threatens the services they provide, and it is essential that we do everything we can to preserve them.

◆ ◆ ◆

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