CHAPTER 6

Biotic Resources

Biotic resources include the raw materials upon which economic production and human life depend, the ecological services that create a habitat capable of supporting human life, and the absorption capacity that keeps us from suffocating in our own waste. As nonrenewable resources are exhausted, human society will come to rely more and more on the self-renewing capacity of biotic resources. It is therefore critically important that we understand the nature of these resources.

As we turn our attention from abiotic resources to biotic ones, we must address a quantum increase in complexity, inevitably accompanied by a quantum increase in ignorance and uncertainty. One level of complexity arises from the intrinsic value we give to living systems. Abiotic resources are almost entirely considered means to various ends, where one of the foremost ends is the sustenance of life, the maintenance of biotic resources. Biotic resources not only enhance human well-being directly, they are also considered by many to be an end in their own right, especially so far sentient creatures. Biotic resources are also physically complex in two ways. First, the processes responsible for the sustained reproduction of individuals, populations, or species are highly complex and poorly understood. Second, individuals, populations, and species interact with other individuals, population, and species, as well as abiotic resources, to create an ecosystem. Ecosystems are extraordinarily complex and dynamic, changing over time in inherently unpredictable ways. The differences between these two types of physical complexity bear closer examination.

ECOSYSTEM STRUCTURE AND FUNCTION

Ecologists look at ecosystems in terms of structure and function, corresponding to the two types of physical complexity mentioned above. This distinction is very relevant to economic analysis. Conventional natural resource economics is essentially the economics of ecosystem structure. Environmental economics focuses on certain ecosystem functions. In reality, structure and function are mutually interdependent, and we need an economics that effectively integrates both. Certainly we must understand the distinctions and interactions between the two if we are to incorporate them into economic analysis.

Ecosystem structure refers to the individuals and communities of plants and animals of which an ecosystem is composed, their age and spatial distribution, and the abiotic resources discussed in Chapter 5.[1] Most ecosystems have thousands of structural elements, each exhibiting varying degrees of complexity. Scientists have learned that when enough separate elements are thrown together into a complex system, a sort of spontaneous order results. One property of such systems is their tendency to generate emergent phenomena, which can be defined as properties of the whole that could not be predicted from an understanding of the individual parts, no matter how detailed that understanding. Complex systems are also characterized by highly nonlinear behavior, which means that we cannot predict the outcomes of large interventions based on an understanding of smaller ones. For example, removing 40% of a species stock from an ecosystem may have a qualitatively different impact than removing 20%—that is, not just twice the known impact of removing 20%.

In an ecosystem, the structural elements act together to create a whole that is greater than the sum of the parts. We refer to these emergent phenomena in ecosystems as **ecosystem functions**,[2] and they include such things as energy transfer, nutrient cycling, gas regulation, climate regulation, and the water cycle. As is typical of emergent properties, ecosystem functions cannot be readily explained by even the most extensive knowledge of system components.[3] Variability, ignorance, and uncertainty play an extremely important role in the analysis of ecosystem structure, and a far greater role in the analysis of ecosystem function. We have a very limited understanding of exactly how ecosystem functions emerge from the complex interactions of ecosystem structure, and thus a difficult time

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[1] It may seem strange to include such things as fossil fuels and mineral deposits as elements of ecosystem structure, but we must not forget that humans are part of the global ecosystem, and these resources affect our ability to thrive.

[2] Whether a particular element of an ecosystem is part of structure or part of function depends on perspective. Organelles are part of the structural components of a cell that enable the cell to function. Cells are structural components of an individual that enable the individual to function. In the same way, individuals are part of the structure of a population, a population is part of the structure of a local ecosystem, an ecosystem is part of the structure of a landscape, and a landscape is part of the structure of the global ecosystem.

[3] E. Odum, *Ecology: A Bridge Between Science and Society*, 3rd ed., Sunderland, MA: Sinauer, 1997.

Box 6-1 Risk, Uncertainty, and Ignorance

Whenever we do not know something for sure, we are uncertain, but there are different types of uncertainty. When I throw dice, I cannot say in advance what the outcome will be, but I do know the possible outcomes and their probabilities. This type of uncertainty is referred to as risk. Pure uncertainty occurs when we know the possible outcomes, but cannot assign meaningful probabilities to them. Ignorance or absolute uncertainty occurs when we do not even know the range of possible outcomes.

In economics, Frank Knight pointed out that risk is a calculable or insurable cost, while pure uncertainty is not. In his view profit—the difference between revenue and calculable risk-adjusted costs—is a return for willingness to endure pure uncertainty. However, Knight was discussing the case where the entrepreneur bore the costs of failure and reaped the rewards of success. In economic decisions regarding exploitation of ecosystems, it is often the entrepreneur who reaps the rewards, while society bears the costs.[1]

Discoveries in quantum physics and chaos theory suggest that uncertainty and ignorance do not result simply from a lack of knowledge, but are irreducible, inherent properties in certain systems. For example, chaos theory shows that even in a deterministic (i.e. nonrandom) system, extremely small differences in initial conditions can lead to radically different outcomes. This has been popularized as the ‘butterfly effect’, in which a butterfly flapping its wings over Japan can create a storm in North America.

Change in highly complex systems is characterized by ignorance, especially over long time spans. We cannot predict evolutionary change in organisms, ecosystems or technologies. For example, while we can predict that computers will continue to get faster and cheaper, we cannot predict what the next big technology will be fifty years from now. Leading experts are often notoriously wrong even when predicting the future of existing technologies. Bill Gates’ once predicted that no one would ever need more than 540 kilobytes of computer memory.

Estimating stocks of natural resources, or reproductive rates for cultivated species is basically a question of risk. Estimating reproductive rates for wild species is a question of uncertainty, since we cannot accurately predict the multitude of factors that affect these reproduction rates, but we do know the range over which reproduction is possible. Estimating ecological thresholds, conditions beyond which ecosystems may flip into alternative states, is a question of pure uncertainty, since we have limited knowledge of ecosystems and cannot predict the external conditions that affect them. Predicting the alternate state into which an ecosystem might flip when it passes an ecological threshold, and how humans will adapt, are cases of absolute ignorance involving evolutionary and technological change.

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[a] *F. H. Knight,* Risk, Uncertainty, and Profit, *Boston: Houghton Mifflin, 1921; Library of Economics and Liberty, Feb. 21, 2002. Online: http://www.econlib.org/library/Knight/knRUPl.html*

predicting and managing the impacts of human actions on these functions. Therefore, a great deal of uncertainty attends decision making involving ecosystem functions. How we choose to treat uncertainty in economic analysis is ultimately a normative (ethical) decision, yet another source of complexity. One of the most important issues concerning any analysis of biotic resources is the degree of uncertainty involved.

Concrete examples always help clarify a concept. To illustrate the links between structure and function, and the implications of complexity, let's focus on a wet tropical forest, the terrestrial ecosystem that exhibits the greatest biodiversity of any yet studied. The forest is composed of individual plants (part of ecosystem structure). Each plant alone has little impact on climate, nutrient cycling, and habitat provision, and may even be unable to reproduce. However, when we bring together hundreds of millions of plants, as in the Amazon or Congo basin, these and other ecosystem functions emerge.

The forest canopy filters out about 98% of the sunlight at ground level, dramatically reducing daytime temperatures. It traps air and insulates, increasing night temperatures under the canopy and maintaining high and constant humidity. Trees absorb the energy of tropical storms, aerate the soil to allow water absorption, and slow water flows—all of which prevent soil and nutrients from being washed out of the system. Trees create the microclimate and habitat essential to the soil fauna that help recycle nutrients, facilitating their reabsorption by the system.

On a regional scale, the water retained by forest structure is absorbed and returned to the atmosphere through evapotranspiration, increasing humidity over the forest. Greater humidity increases the frequency of rainstorms. Estimates for the Amazon forest suggest that it generates up to 50% of its own rainfall, enabling the water-dependent species there to thrive. Without the increased absorption capacity of the soil and the evapotranspiration it facilitates, rainfall would simply drain into the rivers and be flushed from the system forever.

On an even larger scale, forests absorb up to 90% of the solar energy that strikes their canopies. Much of this is released through evapotranspiration and carried high up into the atmosphere, where it is carried into the temperate zones, helping stabilize the global climate (a function provided by carbon sequestration as well).

The species and populations in the forest cannot survive without a stable climate and a steady nutrient flow. Loss of forest structure can degrade forest function to the point where the forest spontaneously declines, creating a positive-feedback loop with potentially irreversible and catastrophically negative consequences.[4] Computer models suggest that

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[4] J. Farley, "Optimal" Deforestation in the Brazilian Amazon; Theory and Policy. Ph.D. Dissertation, Cornell University, 1999.

regional climate change following extensive deforestation in the Amazon will prevent the regrowth of rainforest.[5] Other research suggests that deforestation of 50% of the Amazon could lead to no rainfall at all during much of the year, conditions under which the forest may enter spontaneous decline,[6] or at the very least become dramatically more susceptible to massive fires, such as those that occurred in 1997 in the Amazon, Indonesia, and Mexico.

In other words, ecosystem structure interacts to create ecosystem functions, and the structural elements depend on these functional attributes for their own survival. Owing to the complex nature of the whole system, as structural elements of an ecosystem are lost, in most cases we cannot say for sure to what extent ecosystem functions will be affected. Similarly, as ecosystem functions change in response to human impacts or nonanthropogenic change, we cannot say for certain what the impact will be on ecosystem structure.

> **THINK ABOUT IT!**
> *In Chapter 4, we asked you to make a list of stock-flow and fund-service resources provided by a local ecosystem. Which of these-resources are elements of ecosystem structure? Which are elements of ecosystem function? Do you see any links between these classifications?*

Roughly speaking, conventional and natural resource economics has focused on ecosystem structure, while conventional environmental economics has focused on certain elements of ecosystem function, with a major emphasis on waste absorption capacity and the monetary valuation of other functions. In reality (as many conventional economists are fully aware), ecosystem structure and function are mutually interdependent, and conclusions based on the analysis of one dimension may not apply to the multidimensional case. With this caveat in mind, we now turn our attention to specific categories of biotic resources.

Three basic categories of biotic resources deserve attention. First are **renewable resources**, the elements of ecosystem structure that provide the raw materials for all economic processes. Second are **ecosystem services**, defined as the ecosystem functions of value to humans and generated as emergent phenomena by the interacting elements of ecosystem structure. Third is **waste absorption capacity**, an ecosystem service that is sufficiently distinct from the others to warrant separate treatment.

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[5] R. Monastersky, Amazon Forest Unlikely to Rise from Ashes, *Science News* 11:164 (1990).

[6] I. Walker et al. "Climatic and Ecological Conditions as Key Factors for Ecodevelopment Strategies." In M. Clusener-Godt and I. Sachs, eds. *Brazilian Perspectives on Sustainable Development of the Amazon Region*, Paris: UNESCO and Parthenon Publishing Group, 1995.

Renewable Resources

For simplicity, we can treat biological resources as material stock-flow resources, that is, as elements of ecosystem structure. Like nonrenewable resources, biological stocks can be extracted as fast as humans desire, but they are capable of reproduction. Figure 6.1 depicts a renewable natural resource in stock-flow space: the X-axis depicts the stock, or amount of resource that exists, and the Y-axis depicts the flow. The flow in this case can be the rate of reproduction (or biomass increase) that is likely for any given stock, or the rate of extraction (harvest). A 45-degree dashed line shows the theoretically maximum rate at which we can extract a given stock (i.e., we can extract the entire stock at one time; stock = flow). Actual extraction rates must lie on or below this line. We have also drawn a curve that shows the growth rate of each level of stock, which is also the sustainable yield curve. The sustainable yield is the net annual reproduction from a given stock—for every population of a resource, there is an associated average rate of population increase, and that increase represents a sustainable harvest that can be removed every year without affecting the base population.

We must caution here that there is a great deal of uncertainty concerning the position of this sustainable yield. Not only do we not know at precisely what rate a given population will reproduce; we are also uncertain of the exact population of any given species, though this is more true for animals than for plants, since plants sit still for the census takers while animals do not. While with careful study and census techniques we can assign reasonable probabilities to population estimates for renewable resource stocks (risk), there is greater uncertainty of a qualitatively different type concerning reproduction rates, particularly because these rates depend on a host of "external" factors such as rainfall, abundance of predator and prey species, disease, and so on. In addition, habitat destruction and degradation, pollution, climate change, and other human impacts can profoundly affect the entire curve, shifting it dramatically over time. Thus, in any given year, the actual rate of increase from a given population stock may be wildly different than the average.

As most people are at least vaguely aware, stocks of plants and animals in nature cannot grow forever. Instead, populations reach a point where they fill an available niche, and average death rates are just matched by average birth rates. Populations "stabilize" around an equilibrium, known as the **carrying capacity**. (We use the term *stabilize* loosely, because populations fluctuate in the short term depending on weather conditions, predator-prey cycles, etc. and in the longer term depending on a wide variety of factors. To paraphrase John Maynard Keynes, in the very long term, all species go extinct.) At carrying capac-

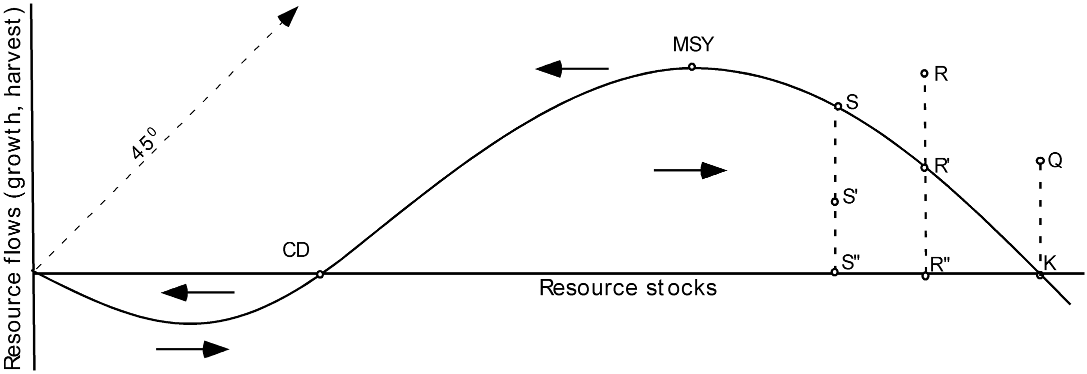

Figure 6.1 • The growth, or sustainable yield, curve.

ity, there is just enough food and habitat to maintain the existing population, and the rate of growth in biomass is zero (point K in Figure 6.1). Obviously, the rate of growth of a stock is also zero when the stock has been driven extinct (the origin in Figure 6.1). In between these two points, things get interesting.

The growth, or sustainable yield, curve for a renewable natural resource indicates the increase in stock over one time period for any given stock (see Figure 6.1). The Y-axis can measure growth or harvest, that is, flows from or to the existing stock depicted on the X-axis. Any harvest up to the total stock is theoretically possible. A harvest at any point on the sustainable yield curve, such as S, is just equal to the growth in the stock, and hence has no net impact on stocks. Harvests above the sustainable yield curve deplete the resource, and harvests below the curve lead to an increase in the stock, as indicated by the arrows. For example, a harvest at R will reduce the stock to S″, and a harvest at S′ will allow the stock to increase to R″. CD represents the critical depensation level, which is the level below which a species or stock cannot sustain itself even in the absence of harvest. The **critical depensation** level is equivalent to the **minimum viable population**, and K represents carrying capacity. The graph suggests extremely rapid growth rates—about 30% per time period at **maximum sustainable yield (MSY)**, which is the average or maximum catch that can be removed under existing environmental conditions over an indefinite period without causing the stock to be depleted, assuming that removals and natural mortality are balanced by stable recruitment and growth. While this may be appropriate for small, rapidly reproducing species, growth rates for many economically important species are on the order of 1% per year or less.

THINK ABOUT IT!

Prior to the arrival of humans in North America, where on the graph in Figure 6.1 would you locate American bison populations? Ten thousand years later, approximately where on the graph do you think bison harvests occurred? After the introduction of the horse, do you think they occurred? After the introduction of the rifle? After the settling of the frontier by Europeans? What impact would the conversion of the Great Plains to agriculture have on the sustainable yield curve for bison?

What happens when we remove some fish, for instance, from a population at carrying capacity? In terms of the graph, we represent this as a harvest at point Q. As there is zero net productivity at our starting point K, harvest Q reduces the stock of fish by the quantity Q-K, and we find ourselves at stock R″. At the lower population stock, there are fewer fish competing for available food, shelter, and breeding grounds, and the remaining fish get more of each than they would under more crowded conditions. This greater resource abundance per individual leads to increased growth rates and fertility. With less competition for spawning areas, a higher percentage of eggs are laid in desirable locations, thereby increasing recruitment.[7] In addition, most species grow fastest in their youth (as a percentage of biomass) and slower as they age. If we harvest larger, older fish, the remaining population has a higher percentage of recruits and potentially faster net growth.

At stock R″, we could continue annual harvests forever at point R′, just equal to the annual rate of increase of the stock. Any harvest below the sustainable yield curve would be less than the annual growth rate. Flows can accumulate into stocks, and the population would increase. Any harvest above the sustainable yield curve would reduce the stock even further. The arrows above and below the curve indicate the direction of change in stock for harvests in each of these regions. For example, a harvest at point R would reduce the population to stock S″. At S″, per-capita resource abundance would be even greater than at R″, increasing net annual growth and sustainable harvest from R′ to S.

Over a certain range, lower population stocks can generate higher sustainable yields, but this obviously cannot go on forever. Eventually, the breeding population is insufficient to sustain high yields. Insufficient numbers of eggs lead to insufficient recruits, reducing yield in spite of superabundant resources per individual within the population. This means that at some point there is a maximum sustainable yield, MSY on Figure

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[7] Note that a harvest at point R decreases the stock in the subsequent period by an amount equal to R-R′ (as measured on the Y-axis), and a harvest at point S′ increases the next period's stock by S-S′. Thus, R-R′ and S-S′ as measured on the Y-axis equal S″-R″ as measured on the X-axis.

Box 6-2 CRITICAL DEPENSATION, MAXIMUM SUSTAINABLE YIELD, AND UNCERTAINTY

Using the notion of maximum sustainable yield to help communicate ideas in ecological economics is a far cry from using the concept as a tool in resource management. In reality, the MSY will vary dramatically from year to year in response to climatic cycles such as the El Niño Southern Oscillation (ENSO), changes in populations of predator and prey species of the species of interest, changes in pollution levels, and a broad array of other ecological changes and cycles. Under the most stable of conditions, natural variability can mask the effects of economic exploitation, and the scale of human impacts is rapidly changing the global ecosystem. Science relies on replication and controls, and neither of these is possible when dealing with a unique species in a highly complex and rapidly changing ecosystem. We cannot scientifically estimate MSY accurately enough for use in resource managements.[a]

Where the critical depensation point lies, and whether or not one exists for a given species or population, is similarly marked by extreme uncertainty. When a population becomes small enough, it is more susceptible to stochastic events and the negative impacts of inbreeding. For the North American passenger pigeon, probably once the most numerous bird on Earth, numbering in the billions but driven extinct in a matter of decades, it appears the minimum viable population was quite high, perhaps because of its colonial nesting habit. At the other extreme, the Mauritius Kestrel has rebounded from a known population of 6 in 1974 to a present population of over 600, though it would have almost certainly gone extinct without substantial conservation efforts, and inbreeding may make it highly susceptible to disease or other stochastic shocks. There is currently a debate over whether or not the blue whale and some populations of North Atlantic cod are below their level of critical depensation. Obviously, experiments to scientifically determine critical depensation points could not be replicated, as the first trial could wipe out the species in question.

On the other hand, uncertainty as to where the MSY is does not mean that we are not overshooting it, nor does it relieve policy makers of the responsibility to decide acceptable levels of offtake. As a general rule, the higher the uncertainty, especially in the presence of irreversibility (extinction), the more conservative (i.e., lower) should the allowed offtake be.

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[a] *D. Ludwig, R. Hilborn, and C. Walters. Uncertainty, Resource Exploitation, and Conservation: Lessons from History,* Science *260:17, 36 (1993).*

6.1. (Again, we caution that the MSY may vary dramatically from year to year, and there is probably no way we can accurately estimate it in any given year. Although it is useful as a pedagogical device, it has very little value as a calculating device for setting annual quotas.[8] If harvests continue to be greater than annual yield, the population will continue to fall. Eventually, fish will become too scarce to find each other for breeding, and other ecological mechanisms (many only poorly understood) can break down. This means that at some population above zero, we may reach a minimum viable population, at which point the rate of growth is zero. Below this point the population enters into spontaneous decline; that is, death rates exceed birth rates.

Note that the sustainable yield curve enters into negative numbers below the critical depensation point. This means that in order to sustain the population, a negative harvest is required; that is, recruits have to be placed into the system every year just to maintain the existing stock. Harvest is still possible anywhere below the 45-degree line, but this will simply lead to even more rapid extinction (or extirpation) of the population. Unfortunately, we do not know where the critical depensation point occurs and can only make very rough (and highly contentious) estimates of where the maximum sustainable yield occurs.

The same basic concepts explained here apply to plant species or even plant communities. For example, what happens when we clear some trees from a virgin forest for timber? Light, water, and nutrients become available to the other trees already there, accelerating their growth, and space becomes available for new seedlings to sprout. This process can initially speed up the growth rate and increase the sustainable yield of a forest. Soon, however, sources of new seeds become more distant from the cleared land, and recruitment slows. Nutrients are lost from the soil as trees are removed. Trees of the same species are too far apart to cross-pollinate, resulting in sterile seeds or the problems of inbreeding. The sustainable yield begins to fall. And as we described above, the removal of ecosystem structure can dramatically affect ecosystem function, with the potential of further reducing the capacity of the forest to reproduce itself. Thus, like animal populations, a stock of forest will show a maximum sustainable yield and may exhibit critical depensation.

We will return to this analysis in Chapter 12 when we examine the microeconomics of biotic resource allocation.

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[8] D. Ludwig, R. Hilborn, and C. Walters. Uncertainty, Resource Exploitation, and Conservation: Lessons from History, *Science* 260:17, 36 (1993).

Box 6-3 CASSOWARIES AND CRITICAL DEPENSATION OF ECOSYSTEMS

In the rainforests of northeastern Australia, up to 100 species of large seeded fruit trees depend almost entirely on a single bird species for distribution. This bird, the cassowary, is a large ratite, an ostrich-like bird that lives in the forest. It is the only animal known in the region capable of swallowing and transporting very large seeds, up to 2 kg of which can be found in a single scat. Evidence suggests that some seeds must pass through the digestive tract of a cassowary before they can germinate.

Cassowaries need large home territories to survive, especially in the highland forests. As forests are cleared in a patchwork pattern, few areas remain that can sustain a viable cassowary population. Without cassowaries, many trees in the region will be unable to disperse, and some may not even be able to germinate. Eventually, these species are likely to go extinct. Other plants and animals depend on these species, and they too will go extinct, igniting a chain reaction of extinction in species that may in turn depend on them. The net result could be a dramatic change in forest composition, leading to a qualitatively different ecosystem. The entire process, however, could take a very long time. It might not be noticed until centuries after it is too late.[a]

Such examples of mechanisms for critical depensation are just a few of the possibilities that have been proposed. Again, we must emphasize that we really have little idea where maximum sustainable yields or critical depensation points lie. Ignorance, uncertainty, and variability are our constant companions in the real world.

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[a] *Bentrupperbaumer, J. Conservation of a rainforest giant. Wingspan, 8)Dec.): 1–2. (1992). Also extensive personal communications.*

ECOSYSTEM SERVICES

In our discussion of ecosystem structure and function, we explained why forests need the functions generated by forests to survive, but we also hinted at the presence of extensive benefits that ecosystem functions provide for humans. *We call an ecosystem function that has value to human beings an ecosystem service*. For example, forested watersheds help maintain stable climates necessary for agriculture, prevent both droughts and floods, purify water, and provide recreation opportunities—all invaluable services for watershed inhabitants. But ecosystems provide many more services, of course. Unfortunately, we are unsure exactly how ecosystem structure creates ecosystem services, and we are often completely unaware of the services they generate. For example, prior to the 1970s, most people were unaware that the ozone layer played a critical role in making our planet habitable.[9] If we also take into account the tightly interlocking nature of ecosystems, it's safe to say that humans benefit in some way from almost any ecosystem function.

We just described forests as a stock of trees that generates a flow of trees. Now we want to look at the forest as a creator of services; as such, they are very different from a stock of trees. A stock of trees can be harvested at any rate; that is, humans have control over the rate of flow of timber produced by a stock of trees. Trees can also be harvested and used immediately, or stockpiled for later use. Ecosystem services are fundamentally different. We cannot use climate stability at any rate we choose—for example, drawing on past or future climate stability to compensate for the global warming we may be causing today. Nor can we stockpile climate stability for use in the future. Nor does climate stability become a part of what it produces. If timber is used to produce a chair, the timber is embodied in that chair. If climate stability is used to produce a crop of grain, that grain in no way embodies climate stability. Furthermore, climate stability is not altered by the production of a crop of grain (unless perhaps the grain is grown on recently deforested land, but still it is the deforestation and not the grain that affects climate stability).

Intact ecosystems are funds that provide ecosystem services, while their structural components are stocks that provide a flow of raw materials. However, recall that stock-flow resources are used up and fund-service resources are worn out. But when ecosystems provide valuable services, this does not "wear them out." The fact is, however, that ecosystems would "wear out" if they did not constantly capture solar energy to renew themselves. The ability of ecosystem fund-services to reproduce themselves distinguishes them in a fundamental way from manmade fund-services. Depreciating machines in a factory do not automatically reproduce new machines to replace themselves.

Example of ecosystem services provided by a forest may help clarify the concept. Costanza et. al. describe 17 different goods and services generated by ecosystems.[10] Forests provide all of these to at least some degree. Of these, food and raw materials are essentially stock-flow variables. The remaining fund-service variables included are described in Table 6.1.

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[9] As further evidence of the extreme uncertainty concerning ecosystem function and human impacts upon it, in 1973 physicist James Lovelock, famous for the Gaia hypothesis, to his later regret stated that fluorocarbons posed no conceivable hazard to the environment. M. E. Kowalok, Common Threads: Research Lessons from Acid Rain, Ozone Depletion, and Global Warming, *Environment* 35 (6): 12–20, 35–38 (1993).

[10] R. Costanza et al., "The Value of the World's Ecosystem Services and Natural Capital," *Nature,* Vol. 387 (1997), p. 256, Table 2.

Table 6.1

EXAMPLES OF SERVICES PROVIDED BY ECOSYSTEMS

Ecosystem Service	Examples from Forests
Gas regulation	Trees store CO_2 and growing trees create O_2; forests can clean SO_2 from the atmosphere.
Climate regulation	Greenhouse gas regulation; evapotranspiration and subsequent transport of stored heat energy to other regions by wind; evapotranspiration, cloud formation, and local rainfall; affects of shade and insulation on local humidity and temperature extremes.
Disturbance regulation	Storm protection, flood control (see water regulation), drought recovery, and other aspects of habitat response to environmental variability mainly controlled by vegetation structure.
Water regulation	Tree roots aerate soil, allowing it to absorb water during rains and release it during dry times, reducing risk and severity of both droughts and floods.
Water supply	Evapotranspiration can increase local rainfall; forests can reduce erosion and hold stream banks in place, preventing siltation of in-stream springs and increasing water flow.
Waste absorption capacity	Forests can absorb large amounts of organic waste, and filter pollutants from runoff; some plants absorb heavy metals.
Erosion control and sediment retention	Trees hold soil in place, forest canopies diminish impact of torrential rainstorms on soils, diminish wind erosion.
Soil formation	Tree roots grind rocks; decaying vegetation adds organic matter.
Nutrient cycling	Tropical forests are characterized by rapid assimilation of decayed material, allowing little time for nutrients to run off into streams and be flushed from the system.
Pollination	Forests harbor insects necessary for fertilizing wild and domestic species.
Biological control	Insect species harbored by forests prey on insect pests.
Refugia or habitat	Forests provide habitat for migratory and resident species, create conditions essential for reproduction of many of the species they contain.
Genetic resources	Forests are sources for unique biological materials and products, such as medicines, genes for resistance to plant pathogens and crop pests, ornamental species.
Recreation	Eco-tourism, hiking, biking, etc.
Cultural	Aesthetic, artistic, educational, spiritual and/or scientific values of forest ecosystems.

THINK ABOUT IT!

Of the ecosystem services in Table 6.1, which are rival and which are excludable? Which would be impossible to make excludable?

Again we emphasize that the precise relationship between the quantity and quality of an ecosystem fund and the services it provides is highly uncertain and is almost certainly characterized by nonlinearities, thresholds, and emergent properties. We can say with reasonable confidence that the larger an ecosystem fund and the better its health, the more services it is likely to generate. As we deplete or degrade a complex ecosystem fund, we really cannot predict what will happen with any reasonable probability. Since we have defined service as an anthropocentric concept, we do know that it can be dramatically affected by human presence and use and not just by abuse. For example, a highly degraded forest in an urban setting may offer more water regulation and more recreational and cultural services (as measured by benefits to humans) than a pristine forest remote from human populations. Forests near orchards or other insect-pollinated crops may offer far more valuable pollination services.

Perhaps even more critical for the economic problem of efficient allocation of ecosystem services is their spatial variation. To use an example already described, large tropical forests can regulate climate at the local level, the regional level, and the global level. Flood control and water purification provided by forests may only benefit select populations bordering local rivers and floodplains, and the provision of habitat for migratory birds may primarily benefit populations along the migratory pathways.

Ecosystem services have some other characteristics that make them extremely important economically. Probably most important, it is unlikely that we can develop substitutes for most of these services, including their providing suitable habitat for humans. We scarcely understand how these services are generated, and we are not aware of all of them. At the cost of some $200 million, a billionaire named Edward Bass initiated the Biosphere Two project in Arizona to see if he could develop substitutes for these services sufficient to sustain only eight people. The project failed. Imagine creating substitutes for billions of people! In addition, most ecosystem services are nonrival—if I benefit from a forest's role in reducing floods, providing habitat for pollinators, or regulating atmospheric gases, it does not diminish the quantity or quality of those services available to anyone else. Many ecosystem services (though certainly not all) are nonexcludable by their very nature as well.

The Relationship Between Natural Capital Stocks and Funds

In review, the structural elements of an ecosystem are stocks of biotic and abiotic resources (minerals, water, trees, other plants and animals), which when combined together generate ecosystem functions, or services. The use of a biological stock at a nonsustainable level in general also depletes a corresponding fund and services it provides. Hence, when we harvest trees from a forest, we are not merely changing the capacity of the forest to create more trees, but are also changing the capacity of the forest to create ecosystem services, many of which are vital to our survival. The same is true for fish we harvest from the ocean, except we know even less about the ecosystem services produced by healthy oceanic ecosystems.

The relationship between natural capital stock-flow and fund-service resources illustrates one of the most important concepts in ecological economics: It is impossible to create something from nothing; all economic production requires a flow of natural resources generated by a stock of natural capital. This flow comes from structural components of ecosystems, and the biotic stocks are also funds that produce ecosystem services. Therefore, an excessive rate of flow extracted from a stock affects not only the stock and its ability to provide a flow in the future, but also the fund to which the stock contributes and the services that fund provides. Even abiotic stocks (i.e., elements and fossil fuels) can only be extracted and consumed at some cost to the ecosystem. In other words, production requires inputs of ecosystem structure. Ecosystem structure generates ecosystem function, which in turn provides services. All economic production thus has an impact on ecosystem services, and because this impact is unavoidable, it is completely internal to the economic process.

WASTE ABSORPTION CAPACITY

But this is only half the story. The laws of thermodynamics ensure that raw materials once used by the economic system do not disappear but instead return to the ecosystem as high-entropy waste. They also ensure that the process of producing useful (ordered) products also produces a more than compensating amount of disorder, or waste. Much of this waste can be assimilated by the ecosystem. Indeed, waste assimilation and recycling are ecosystem services on which all life ultimately depends. However, as a fund-service, waste absorption occurs only at a fixed rate, while conversion of stock-flow resources into waste occurs at a rate we can choose. Waste absorption capacity is a sink for which we have control over the flow from the faucet, but not over the size of the drain. The removal of ecosystem structure also affects the ability of the ecosystem to process waste. If we discharge waste beyond the ecosystem's capacity to absorb it, we can reduce the rate at which an ecosystem can absorb waste, which makes the waste accumulate more quickly. In time, the waste buildup will affect other ecosystem functions, though we cannot always predict which services will be affected and when.

A specific example can help illustrate these points. When we first begin to dump wastes, such as raw sewage and agricultural runoff, into a pristine lake, they will be heavily diluted and cause little harm. Higher waste loads may threaten humans who use the lake with intermittent health problems from bacteria and noxious chemicals contaminating the sewage, and water becomes unsuitable for drinking without prior treatment. Increasing nutrients allow bacterial and algal populations to thrive, increasing the ability of the system to process waste, but reducing a number of other ecosystem services. Fish will begin to accumulate noxious compounds present in the waste stream and become inedible. Pollution-sensitive species will be extirpated. Yet more waste may make the water unsuitable for drinking even after extensive processing, and eventually it will become too contaminated for industrial use. Excess nutrients eventually lead to eutrophication, where algal and bacterial growth absorbs so much oxygen during the night[11] and during the decay process that fish, amphibians, and most invertebrate species die out. Birds and terrestrial animals that depend on the lake for water and food will suffer. With even greater waste flows, even algae may fail to thrive, and we have surpassed the waste absorption capacity of the system. Waste begins to accumulate, further decreasing the ability of algae to survive, and leading to a more rapid accumulation of waste even if the waste flow is not increased any more. The system collapses.

Just prior to the point where waste flows exceed the waste absorption capacity, a reduction in flows will allow the system to recuperate. After that point, they will not. Similar dynamics apply to other ecosystems. If the ecosystem in question provides critical life-support functions, either locally or globally, the costs of exceeding the waste absorption capacity of an ecosystem are basically infinite, at least from the perspective of those humans it sustains.

In general, ecosystems have a greater ability to process waste products from biological resources, and a much more limited capacity to absorb manmade chemicals created from mineral resources. This is because ecosystems evolved over billions of years in the presence of biological wastes. In contrast, products such as halogenated cyclic organic compounds and plutonium (two of the most pernicious and persistent pollutants known (are novel substances with which the ecosystem has had no evolutionary experience, and therefore has not adapted.

In contrast to many ecosystem services, waste absorption capacity is rival. If I dump pollution into a river, it reduces the capacity of the river

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[11] While growing plants are net producers of oxygen and absorbers of CO_2, they also require oxygen for survival. During the day, photosynthesis generates more oxygen than the plants consume, but at night they consume oxygen without producing any. Average oxygen levels may be higher, but the lowest levels determine the ability of fish and other species to survive.

to assimilate the waste you dump in. It is also fairly simple to establish institutions that make waste absorption excludable, and many such institutions exist.

The bottom line is that the laws of thermodynamics tell us that natural resources are economic throughputs. We must pay close attention to where they come from, and where they go.

Table 6.2 summarizes some of the important characteristics of the three biotic resources. We will discuss these characteristics and examine their policy relevance in greater detail in Chapter 12 and Part VI.

The points to take away from this chapter deserve reiteration. First, humans, like all animals, depend for survival on the ability of plants to capture solar energy in two ways: directly as a source of energy, and indirectly through the life-support functions generated by the global ecosystem, which itself is driven by the net primary productivity of plants. There are no substitutes for these life-support functions. Second, every act of economic production requires natural resource inputs. Not only are these inputs being used faster than they can replenish themselves; when these structural elements of ecosystems are removed, they diminish ecosystem function. Third, every act of economic production generates waste. Waste has a direct impact on human well-being and further diminishes ecosystem function. While the removal of mineral resources may have little direct impact on ecosystem function, the waste stream from their extraction and use is highly damaging to ecosystems and human well-being in the long run. As the economy expands, it depletes nonrenewable resources, displaces healthy ecosystems and the benefits they provide, and degrades remaining ecosystems with waste outflows.

Biotic resources are unique because they are simultaneously stocks and funds, and their ability to renew themselves is a fund-service. This means

Table 6.2

ECONOMIC CHARACTERISTICS OF BIOTIC RESOURCES

Biotic Resource	Stock-Flow or Fund-Service	Excludable (regime-dependent)	Rival	Rival Between Generations	Substitutability
Renewable Resources	Stock-flow	Yes	Yes	Depends on rate of use	High at margin, ultimately nonsubstitutable
Ecosystem Services	Fund-service	No	For most, no	No	Low at margin, nonsubstitutable
Waste Absorption Capacity	Fund-service	Can be made excludable	Yes	Depends on rate of use	Moderate at margin, nonsubstitutable

that ultimately economic scale is determined by the amount of fund-services provided in a given year, where one of those fund-services is the ability of renewable natural resources to renew. Biotic resources have a particularly large impact on scale because they ultimately have no substitutes, and we cannot survive without them.

BIG IDEAS to remember

- Ecosystem structure
- Ecosystem function
- Ecosystem services
- Stock-flow and fund-service resources
- Risk, uncertainty, ignorance
- Carrying capacity
- Minimum viable population
- Critical depensation
- Maximum sustainable yield
- Waste absorption capacity