Box 6-3 CASSOWARIES, MINIMUM VIABLE POPULATIONS, 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 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.

[a] *J. Bentrupperbaumer, 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.[8] 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, it is 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.

Examples of ecosystem services provided by a forest may help clarify the concept. Costanza et al. describe 17 different goods and services generated by ecosystems.[9] Forests provide all of these to at least some degree. Of these, food and raw materials are essentially stock-flow variables, though their ability to regenerate is a fund-service. The remaining fund-service variables included are described in Table 6.1.

[8]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).

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

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; effects 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 controlled mainly 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, creating 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	Ecotourism, hiking, biking.
Cultural	Aesthetic, artistic, educational, spiritual, and 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 benefit only select populations bordering local rivers and floodplains, and the provision of habitat for migratory birds may benefit primarily 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 the provision of 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 the services it provides. Hence, when we harvest trees from a forest, we are not merely reducing the stock of 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 be extracted and consumed only 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[10] 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.

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, it may 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 the 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

[10]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, but 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	Can Be Made Excludable	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	For most, no	For most, no	No	Low at margin, nonsubstitutable
Waste Absorption Capacity	Fund-service	Yes	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

Box 24-2 METHODS FOR MONETARY VALUATIONS OF ECOSYSTEMS

Several methods are available for putting dollar values on the nonmarketed goods and services provided by ecosystems. Many of these are appropriate for valuing only a small subset of services. Most textbooks in environmental economics provide an adequate introduction to these methods. We recommend as a good starting point the Web site "Ecosystem Valuation" at http://www.ecosystemvaluation.org, where the following methods are listed:

- *Market Price Method:* Estimates economic values for ecosystem products or services that are bought and sold in commercial markets.
- *Productivity Method:* Estimates economic values for ecosystem products or services that contribute to the production of commercially marketed goods.
- *Hedonic Pricing Method:* Estimates economic values for ecosystem or environmental services that directly affect market prices of some other good.
- *Travel Cost Method:* Estimates economic values associated with ecosystems or sites that are used for recreation. Assumes that the value of a site is reflected in how much people are willing to pay to travel to visit the site.
- *Damage Cost Avoided, Replacement Cost, and Substitute Cost Methods:* Estimate economic values based on the costs of avoided damages resulting from lost ecosystem services, the costs of replacing ecosystem services, or the costs of providing substitute services.
- *Contingent Valuation Method:* Estimates economic values for virtually any ecosystem or environmental service. The most widely used method for estimating nonuse or "passive use" values. Asks people to directly state their willingness to pay for specific environmental services, based on a hypothetical scenario.
- *Contingent Choice Method:* Estimates economic values for virtually any ecosystem or environmental service. Based on asking people to make tradeoffs between sets of ecosystem or environmental services or characteristics. Does not directly ask for willingness to pay; this is inferred from tradeoffs that include cost as an attribute.
- *Benefit Transfer Method:* Estimates economic values by transferring existing benefit estimates from studies already completed for another location or issue.

tribution. Conventional economists argue that the question is not one of distribution but rather one of efficient allocation. If a resource will be sufficiently more valuable in the future than in the present, it should be saved for the future. Therefore, maximizing the net present value (NPV)