CHAPTER 9

Ecological Economics: Basic Concepts

Chapter 9 Focus Questions

- Are natural resources a form of capital?
- How can we account for and conserve resources and environmental systems?
- What limits the scale of economic systems?
- How can we sustain economic well-being and ecosystem health in the long term?

9.1 AN ECOLOGICAL PERSPECTIVE

The relationships between economic and environmental issues can be viewed from a variety of perspectives. In Chapters 3–8 we applied concepts derived from standard economic analysis to environmental issues. The school of thought known as **ecological economics**, however, takes a different approach. Ecological economics attempts to redefine basic economic concepts to make them more applicable to environmental problems. As noted in Chapter 1, this often means viewing problems from a macro rather than a micro perspective, focusing on major ecological cycles and applying the logic of physical and biological systems to the human economy, rather than viewing ecosystems through a lens of economic analysis:

methodological pluralism the view that a more comprehensive understanding of problems can be obtained using a combination of perspectives.

> The fundamental, original premise of ecological economics is to insist on seeing the human economy as embedded in and part of Earth's biogeochemical systems.[1]

Unlike standard economic analysis, ecological analysis does not have a single methodological framework based on markets. Ecological economist Richard Norgaard has identified this approach as **methodological pluralism**, maintaining that "multiple insights guard against mistaken action based on one perspective."[2] ("Methodology" means the set of techniques and approaches used to analyze a problem.) Through a combination of different analyses and techniques, we can achieve a more comprehensive picture of the problems that we study.

This pluralist approach means that ecological economics is not necessarily incompatible with standard market analysis. The analyses reviewed in Chapters 3–8 offer many insights that are complementary to a broader ecological perspective. But some of the assumptions and concepts used in market analysis may need to be modified or replaced in order to gain an understanding of the interaction between the economic system and ecological systems.[3]

9.2 NATURAL CAPITAL

One fundamental concept emphasized by ecological economists is **natural capital**. Most economic models of the production process focus on two factors of production: capital and labor. A third factor, usually referred to as "land," is acknowledged but usually has no prominent function in economic models. Classical economists of the nineteenth century, especially David Ricardo, author of *The Principles of Political Economy and Taxation*, were concerned with land and its productivity as a fundamental determinant of economic production.[4] Modern economics, however, generally assumes that technological progress will overcome any limits on the productive capacity of land.

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

Ecological economists have reintroduced and broadened the classical concept of "land," renaming it natural capital. Natural capital is defined as the entire endowment of land and resources available to us, including air, water, fertile soil, forests, fisheries, mineral resources, and the ecological life-support systems without which economic activity, and indeed life itself, would not be possible.

In an ecological economics perspective, natural capital should be considered at least as important as human-made capital as a basis for production. Further, a careful accounting should be made of the state of natural capital and of its improvement or deterioration, and this should be reflected in national income accounting.

Accounting for Changes in Natural Capital

net investment and disinvestment the process of adding to, or subtracting from, productive capital over time, calculated by subtracting depreciation from gross, or total, investment.

Defining natural resources as capital raises an important economic implication. A central principle of prudent economic management is preservation of the value of capital. It is generally desirable to add to productive capital over time, a process that economists call **net investment**. A country whose productive capital decreases overtime (**net disinvestment**) is a country in economic decline.

Sir John Hicks, Nobel laureate in economics and author of *Value and Capital* (1939), defined income as the amount of goods and services that an individual or country can consume over a period while remaining at least as well off at the end of the period as at the beginning. In other words, you cannot increase your income by reducing your capital.

To see what this means in practice, imagine someone who receives an inheritance of $1 million. Suppose that the $1 million is invested in bonds that yield a real return (i.e., return in excess of inflation) of 3 percent. This will give an annual income of $30,000. However, if the recipient of the inheritance decides to spend $50,000 per year from the inheritance, s/he will be spending $20,000 of capital in addition to the $30,000 income. This means that in future years, the income will be reduced, and eventually the capital will be entirely depleted. Clearly, this is different from a prudent policy of living only on income, which would allow the recipient to have an income of $30,000 per year indefinitely.

This principle is generally accepted insofar as human-made capital is concerned. Standard national income accounting includes a calculation of the depletion of human-made capital over time. This **capital depreciation** is estimated annually and subtracted from gross national product to obtain net national product. To maintain national wealth undiminished requires at least enough investment to replace the capital that is depleted each year. We recognize this also by distinguishing between gross and net investment. Net investment is gross investment minus depreciation and can be zero or below zero if insufficient replacement investment occurs. A negative net investment implies a decline in national wealth.

capital depreciation a deduction in national income accounting for the wearing-out of capital over time.

natural capital depreciation a deduction in national accounting for loss of natural capital, such as a reduction in the supply of timber, wildlife habitat, or mineral resources.

But no similar provision is made for **natural capital depreciation**. If a country cuts down its forests and converts them to timber for domestic consumption or export, this enters the national income accounts only as a positive contribution to income, equal to the value of the timber. No accounting is made of the loss of standing forest, either as an economic resource or in terms of its ecological value. From the standpoint of ecological economics, this is a serious omission that must be corrected.[5] Ecological economists have proposed revisions to national income accounting systems so as to include natural capital depreciation (we consider these proposals in detail in Chapter 10).

The Dynamics of Natural Capital

The natural capital concept further implies that a purely economic analysis cannot fully capture the stock and flow dynamics of natural resources. As we saw in Chapters 6 and 7, economists have many techniques for expressing natural resource and environmental factors in monetary terms suitable for standard economic analysis. But this captures only one dimension of natural capital.

The basic laws governing behavior of natural capital elements such as energy resources, water, chemical elements, and life forms are physical laws described in the sciences of chemistry, physics, biology, and ecology. Without specific consideration of these laws, we cannot gain a full understanding of natural capital.

For example, in agricultural systems, soil fertility is determined by complex interactions among chemical nutrients, micro-organisms, water flows, and plant and animal waste recycling. Measuring soil fertility in terms of, say, grain output, will be valid for short-term economic calculations, but may be misleading over the long term as subtler ecological processes come into play. Loss of micronutrients, carbon content, and water retention capacity over time could result in a steady decline in underlying soil fertility, which might go unnoticed because it could be masked by application of more fertilizer in the short term. A purely economic analysis could result in insufficient attention to long-term maintenance of soil fertility.

Thus it is necessary to combine insights from economic analysis with ecological principles when dealing with issues of the maintenance of natural capital. This does not render the economic techniques of Chapters 3–8 irrelevant; rather, they must be complemented by ecological perspectives on natural systems to avoid misleading results. Techniques advocated by ecological economists for natural capital accounting and conservation include the following:

- Physical accounting for natural capital. In addition to the familiar national income accounts, satellite accounts can be constructed to show the abundance or scarcity of natural resources and to estimate their variations from year to year. These accounts can also show pollutant build-up, water quality, soil fertility variations, and other important physical indicators of environmental conditions. Accounts that indicate significant resource depletion or environmental degradation call for measures to conserve or restore natural capital.
- Determination of sustainable yield levels. As we saw in Chapter 4, economic exploitation of natural resources often exceeds ecologically sustainable levels. An ecological analysis of a natural system harvested for human use can help to determine the sustainable yield level at which the system can continue to operate indefinitely. If the economic equilibrium yield exceeds the sustainable yield, the resource is threatened, and specific protective policies are necessary. This has happened with many fisheries and forests, a topic dealt with in Chapters 18 and 19.
- Determination of the absorptive capacity of the environment for human-generated wastes, including household, agricultural, and industrial wastes. Natural processes can break down many waste products over time and reabsorb them into the environment without damage. Other waste and pollutants, such as chlorinated pesticides, chlorofluorocarbons (CFCs), and radioactive waste are difficult or impossible for the environment to absorb. In the case of carbon dioxide, there is a planetary capacity to absorb excess carbon, but this capacity is now being exceeded. In general, scientific analysis can offer a baseline estimate of acceptable levels of waste emissions. This will not necessarily coincide with the economic concept of "optimal pollution levels" introduced in Chapter 3, since it takes into account ecological factors that are not reflected in the market-based analysis of marginal costs and benefits.

physical accounting a supplement to national income accounting that estimates the stock or services of natural resources in physical, rather than economic, terms.

satellite accounts accounts that estimate the supply of natural capital in physical, rather than monetary, terms; used to supplement traditional national income accounting.

resource depletion a decline in the stock of a renewable resource due to human exploitation.

environmental degradation loss of environmental resources, functions, or quality, often as a result of human economic activity.

sustainable yield a yield or harvest level that can be maintained without diminishing the stock or population of the resource.

absorptive capacity of the environment the ability of the environment to absorb and render harmless waste products.

substitutability (of human-made and natural capital) the ability of one resource or input to substitute for another; in particular, the ability of human-made capital to compensate for the depletion of some types of natural capital.

complementarity the property of being used together in production or consumption, for example, the use of gasoline and automobiles.

natural capital sustainability conserving natural capital by limiting depletion rates and investing in resource renewal.

This perspective differs in significant respects from standard economic theory, which generally assumes **substitutability** between resources. For example, industrially produced fertilizer might compensate for loss of fertile soil. The ecological perspective tells us that substitution is not so easy—the natural resource base for economic activity is in a sense irreplaceable, unlike human-made factories or machinery. In the case of fertilizer, heavy applications of fertilizer can deplete other nutrients in the soil as well as pollute waterways with fertilizer runoff.

In many cases, natural capital displays **complementarity** rather than substitutability with manufactured capital—meaning that both are needed for effective production. For example, increasing the stock of fishing boats will be of no use if stocks of fish are depleted (as discussed in Chapters 4 and 13). The essential function of natural capital means that we need to modify standard theories of economic growth to take into account issues of ecological limits and long-term sustainability.[6]

This analysis points toward a general principle of **natural capital sustainability**. According to this principle, countries should aim to conserve their natural capital by limiting its depletion or degradation and investing in its renewal (e.g., through soil conservation or reforestation programs). The difficult and controversial process of translating this general principle into specific policy rules brings into focus the differences between economic and ecological analyses. We deal with some of these questions in more detail in future chapters.

9.3 ISSUES OF MACROECONOMIC SCALE

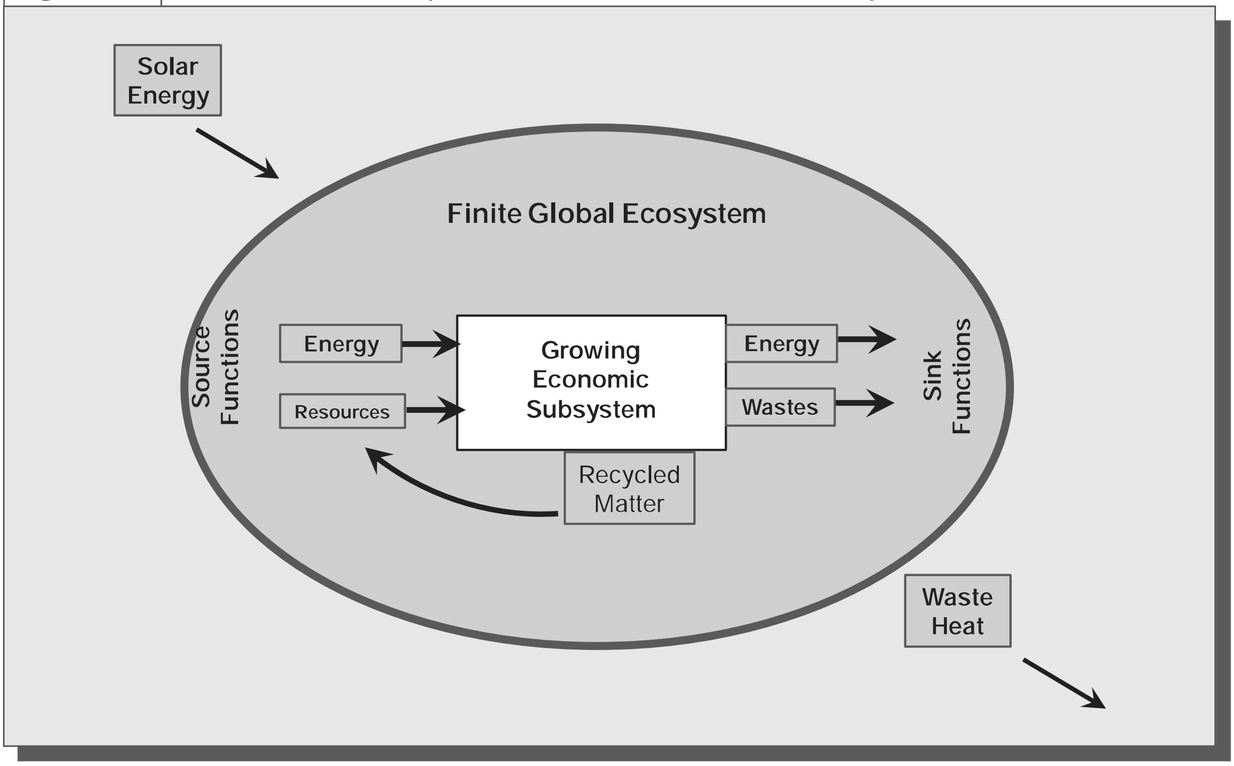
Standard macroeconomic theory recognizes no limitation on an economy's scale. Keynesian, classical, and other economic theories deal with the conditions for equilibrium among the macroeconomic aggregates of consumption, savings, investment, government spending, taxes, and money supply. But with economic growth, the equilibrium level can in theory rise indefinitely, so that a country's gross domestic product (GDP) can multiply tenfold or a hundredfold over time.

optimal macroeconomic scale the concept that economic systems have an optimal scale level beyond which further growth leads to lower well-being or resource degradation.

With a 5 percent growth rate, for example, GDP would double every fourteen years, becoming more than 100 times as large within a century. Even at a 2 percent growth rate, GDP doubles in 35 years, growing sevenfold in a century. From the point of view of mathematical computation of economic equilibrium, such growth poses no problem. But ecological economists, in particular Robert Goodland and Herman Daly, have argued that resource and environmental factors impose practical limits on feasible levels of economic activity and that economic theory must include a concept of **optimal macroeconomic scale**.[7]

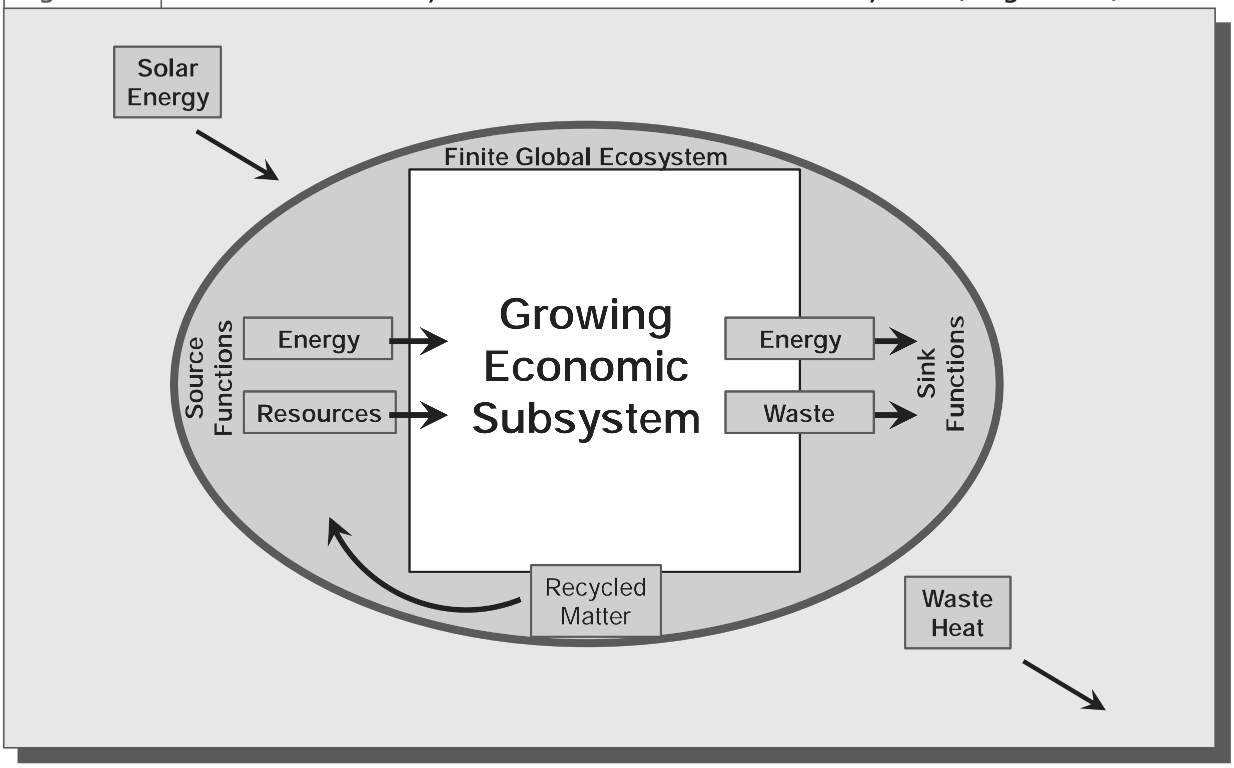
This concept is relevant both for individual economies dependent on limited resource bases and for the global economy. Its implications for the global economy are especially important, because national economies can overcome resource limitations through international trade. The situation is illustrated in Figures 9.1 and 9.2. Figure 9.1, showing a schematic relationship between economic and ecological systems, is similar to Figure 1.2 in Chapter 1. Figure 9.2 shows how the situation changes as the economy grows, with a larger economic subsystem applying significant physical and life-cycle stress on the surrounding ecosystem.

Figure 9.1 The Economic Subsystem Relative to the Global Ecosystem (Small Scale)



Source: Goodland, Daly, and El Serafy, 1992, p. 5.

Figure 9.2 The Economic Subsystem Relative to the Global Ecosystem (Large Scale)



Source: Goodland, Daly, and El Serafy, 1992, p. 5.

The economic system (shown as a rectangle in Figures 9.1 and 9.2) uses both energy and resources as inputs and releases waste energy and other wastes into the ecosystem (shown as a circle). The combined input and waste flows can be called **throughput**.[8] The economic system as shown here is an **open system**, exchanging energy and resources with the global ecosystem within which it is located. The global ecosystem has an inflow of solar energy and an outflow of waste heat, but is otherwise a **closed system**.

> **throughput** the total use of energy and materials as both inputs and outputs of a process.
>
> **open system** a system that exchanges energy or natural resources with another system; the economic system is considered an open system because it receives energy and natural resources from the ecosystem and deposits wastes into the ecosystem.
>
> **closed system** a system that does not exchange energy or resources with another system; except for solar energy and waste heat, the global ecosystem is a closed system.
>
> **scale limit** a limit to the size of a system, including an economic system.
>
> **empty-world and full-world economics** the view that economic approaches to environmental issues should differ depending on whether the scale of the economy relative to the ecosystem is small (an empty world) or large (a full world).
>
> **steady state** an economy that maintains a constant level of natural capital by limiting the throughput of material and energy resources.
>
> **dematerialization** the process of achieving an economic goal through a decrease in the use of physical materials, such as making aluminum cans with less metal.
>
> **decoupling** breaking the correlation between increased economic activity and similar increases in environmental impacts.

As the open economic subsystem grows within the closed planetary ecosystem (shown by the enlarged rectangle in Figure 9.2), its resource needs and waste flows are more difficult to accommodate. The fixed size of the planetary ecosystem places a **scale limit** on economic system growth.

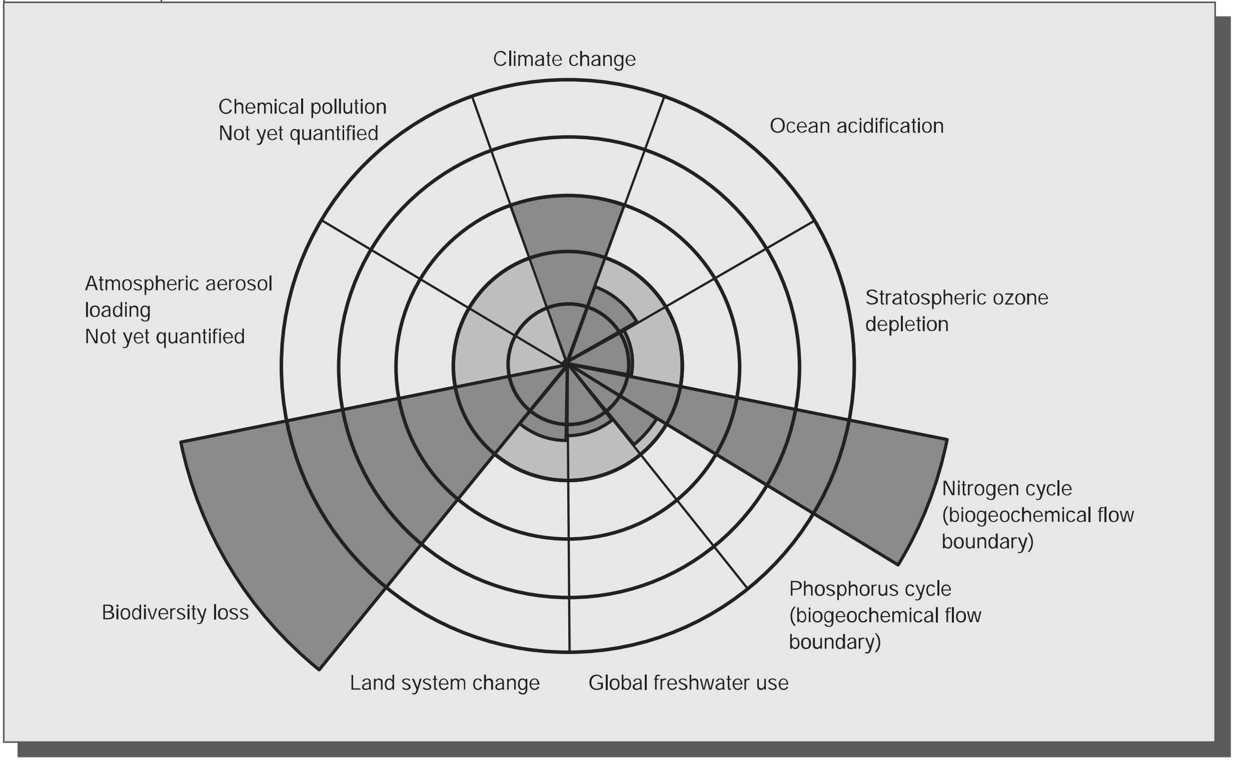
Daly and Goodland have argued that rapid economic growth brought us from **empty-world economics** to **full-world economics**. In the "empty-world" phase, when the economic system is small relative to the ecosystem, resource and environmental limits are unimportant, and the main economic activity is the exploitation of natural resources to build up human-made capital stocks and to expand consumption. At this stage, economic activity is constrained mainly by limited quantities of human-made capital.

In the "full-world" phase, however, when the dramatically expanded human economic system presses against ecosystem limits, the conservation of natural capital becomes far more important. If we do not implement adequate measures to conserve resources and protect the "full-world" environment, environmental degradation will undermine economic activity regardless of how large stocks of human-made capital become.[9] Ultimately, this implies that the economy must adapt from a pattern of growth to a **steady-state** in which population and production rates must stabilize:

> The facts are plain and incontestable: the biosphere is finite, non-growing, and closed (except for the constant input of solar energy). Any subsystem such as the economy, must cease growing at some point and adapt itself to a dynamic equilibrium, something like a steady state. To achieve this equilibrium, birth rates must equal death rates, and production rates of commodities must equal depreciation rates.[10]

This logic refers to the *physical* growth of the economic system, measured in terms of its resource and energy demands and waste flows. It is possible for GDP to grow without higher resource requirements, especially if growth is concentrated in the service sector. Expanded automobile production, for example, requires more steel, glass, rubber, and other material inputs, as well as gasoline to operate the vehicles. But more opera productions or child-care services require few physical resources. Energy and physical resource use may also become more efficient, thus requiring fewer throughputs of resources per unit of output, a process known as **dematerialization** or **decoupling**, discussed in greater detail in Chapter 14. In general, though, growing GDP is

Figure 9.3 Planetary Boundaries



Source: Rockström *et al.*, 2009.

Note: The inner shading represents the proposed "safe operating space" for nine planetary systems. The wedges represent an estimate of the current position for each system. The boundaries in three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle) have already been exceeded and two others (ocean acidification and phosphorous cycle) were close to limits as of 2009.

associated with higher throughput of energy and resources. Ecological economists, therefore, work to develop "a conceptual framework within which macroeconomic stability is consistent with the ecological limits of a finite planet."[11]

Economic activity undoubtedly faces some scale limits. How can we determine whether the economic subsystem is straining the limits of the ecosystem? One way is simply by noting the increased prevalence of large-scale or global environmental problems, such as global climate change, ozone layer destruction, ocean pollution, soil degradation, and species loss.[12] In commonsense terms as well as in ecological analysis, these pervasive problems suggest that important environmental thresholds had been reached by the early twenty-first century. A scientific study of important planetary boundaries found that several of them had already been exceeded, including those for nitrogen, climate, and biodiversity[13] (See Figure 9.3).

Measuring the Relationship Between Economic and Ecological Systems

Ecological economists have developed different approaches to measuring the overall scale of human economic activity. One approach recognizes that both ecological and economic systems rely upon energy to support and expand the functions of life. Living systems obtain solar energy through plant photosynthesis. As the human economic system grows, a larger proportion of this **net primary product of photosynthesis (NPP)** is used directly or indirectly to support economic activity. This appropriation of photosynthetic energy takes place through agriculture, forestry, fisheries, and fuel use. In addition, human activities convert land from natural or agricultural functions for urban and industrial uses, transportation systems, and housing construction.

> **net primary product of photosynthesis (NPP)** the biomass energy directly produced by photosynthesis.
>
> **carrying capacity** the level of population and consumption that can be sustained by the available resource base.

According to recent studies, humans have appropriated about 25 percent of NPP, with much higher rates of 83 percent and 73 percent in cropland and major infrastructure (densely inhabited) areas. The rate doubled during the twentieth century, and is projected to increase further by 2050.[14] This gives another perspective on the "full-world" concept, implying that, particularly for agricultural and biomass production, there are significant planetary limits. These limits can be expressed in terms of **carrying capacity**: the level of population and consumption that can be sustained by the planetary resource base. We will discuss some specific implications of these limits, in areas such as water, agriculture, fisheries, and atmospheric systems, in future chapters.

Another approach for measuring the scale of human activity attempts to capture the multidimensional ways in which people impact the environment in a single index. The ecological footprint (EF) concept, originally developed by Wackernagel and Rees (1996), seeks to convert all human environmental impacts into a measure of the amount of land required to supply all the necessary resources and assimilate all the wastes. In other words, a person's ecological footprint is the amount of land required to support his or her lifestyle.

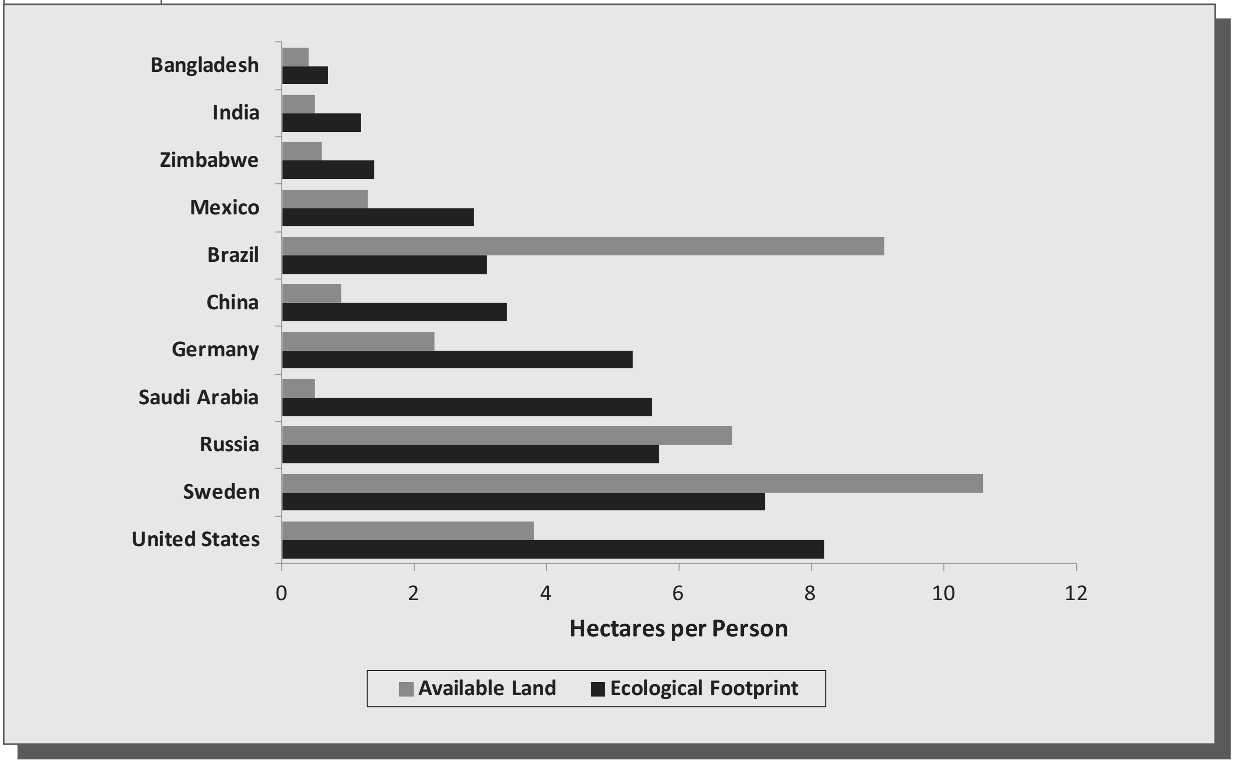
From a policy perspective, converting all environmental impacts into a single index may have some advantages, such as being able to determine whether overall impacts are increasing or decreasing. Measuring ecological footprints in land area units (hectares or acres) is relatively easy to understand and interpret. Also, the necessary data for the measurement of ecological footprints are readily available, on various scales from an individual to a country, and for most countries of the world, allowing for consistent measurement and comparisons.

Some effects convert easily to land-area footprints. For example, demand for meat converts to pasture area needed to raise livestock. Other impacts are more difficult to translate into land-area equivalents. For instance, carbon dioxide emissions from burning fossil fuels are accounted for in the EF approach based on the area of vegetation that would be required to absorb the carbon emitted. Calculation of a country's ecological footprint requires data on more than 100 factors, including demand for food products, timber, energy, industrial machinery, office supplies, and vehicles.

Comparing a region's ecological footprint to its available land helps determine whether the region's ecological impact is sustainable. Figure 9.4 presents the per-capita ecological footprints and available productive land for selected countries. The per-capita ecological footprints are much higher in developed countries than in developing countries. The average American requires about 8 hectares to support his or her lifestyle, while the average Indian requires less than one hectare.

Most countries, developed or developing, are currently running an ecological deficit. For example, we see in Figure 9.4 that the ecological footprint of the United States exceeds its available land by a factor of more than two. China's ecological footprint is nearly four times larger than its available land, and Saudi Arabia's footprint is 11 times greater than its land. The only countries in Figure 9.4 with an ecological footprint less than their available land are

Figure 9.4 **Per-Capita Ecological Footprint and Available Land, Selected Countries, 2012**



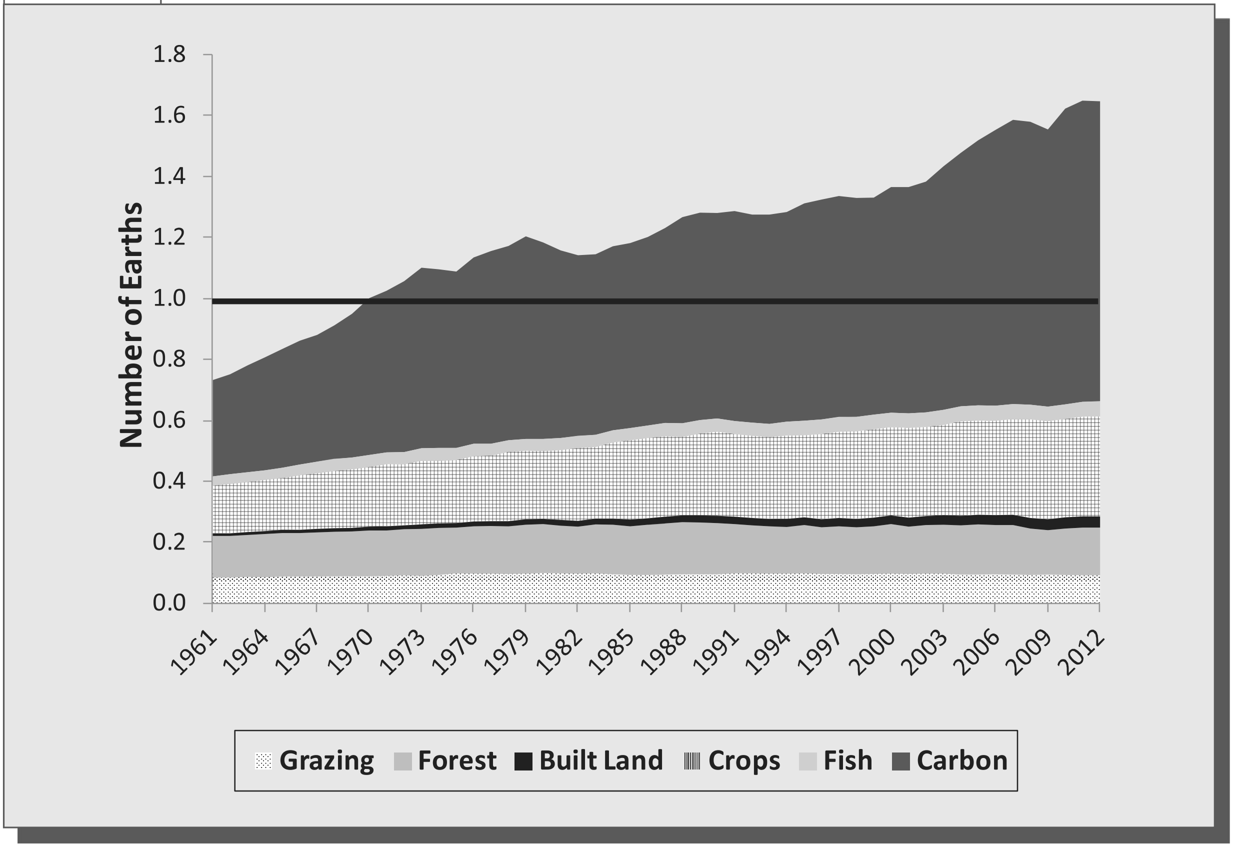
Source: Global Footprint Network, 2016.

Brazil, Russia, and Sweden. Note that this doesn't necessarily imply that these countries have pursued sustainable environmental policies. In the case of Russia in particular, per-person ecological impacts are relatively high but the total available land is even greater (Russia has more land area than any other country).

At the global level humanity's ecological footprint is 1.64 times greater than the available land on the planet. Thus the global ecological footprint, measured in terms of the number of earth-sized planets required to supply humanity's resources and assimilate its wastes, exceeds the one earth available to us, implying a long-term net depletion of natural capital. We see this in Figure 9.5, which breaks down humanity's ecological footprint into different types of impacts. About 60 percent of humanity's total ecological footprint is attributed to carbon emissions, and another 20 percent is related to the growing of crops.

The overall implication of Figure 9.5 is that humanity needs to reduce its ecological footprint in order to achieve sustainability. But the results also provide some guidance on policy efforts to achieve sustainability. Specifically, efforts to reduce carbon emissions, even while keeping other impacts constant, could be sufficient to reduce humanity's ecological footprint to less than one earth. Climate scientists estimate that in order to limit global warming to no more than 2°C we'll need to reduce global carbon emissions by 40–70 percent by 2050, and eventually to near zero by the end of the century (discussed in detail in Chapters 12 and 13).[15] A 70 percent reduction in carbon emissions, again while keeping other impacts constant, would reduce humanity's ecological footprint from 1.64 earths to 0.96 earths. Of course this doesn't imply that we should not direct effort toward reducing other ecological impacts, but it does indicate that we will not achieve a sustainable global footprint without significant reductions in carbon emissions.

Figure 9.5 Global Ecological Footprint, by Impact Type



Source: Global Footprint Network, 2016.

9.4 LONG-TERM SUSTAINABILITY

We have already mentioned sustainability in terms of natural capital. But how can this term be defined more precisely? We want to limit the loss or degradation of natural capital and to invest in its conservation and renewal. Taken in its strictest sense, this would mean that we could never use any depletable resource or conduct any economic activity that would substantially alter natural systems. In a world of more than 7 billion people, largely either industrialized or rapidly industrializing, this is clearly impossible. But unrestrained resource use and ever-increasing waste generation is also unacceptable. How can we strike the balance?

We have already examined elements of the standard economic answer to this question. The theories of external economies, resource allocation over time, and common-property and public goods management, which we outlined in Chapters 3–5, offer economic principles on when to use and when to conserve resources and on "optimal" pollution levels. In the long-term global context, however, these theories may be insufficient. Oriented toward individual markets, they may fail to guarantee environmental sustainability at the macroeconomic level. We need guidelines for overall conservation of the national and global resource bases. Within these guidelines, market solutions to specific resource and environmental management problems will become relevant.

> **strong sustainability** the view that natural and human-made capital are generally not substitutable and, therefore, natural capital levels should be maintained.

We can distinguish between the concepts of **strong sustainability** and **weak sustainability**. (The use of the terms "strong" and "weak" in this context refers to how demanding our assumptions are and does not imply that one is necessarily better or worse than the other.) Strong sustainability is based on an assumption of very limited substitutability between natural and human-made capital. Weak sustainability assumes that natural and human-made capital are generally substitutable.[16]

weak sustainability the view that natural capital depletion is justified as long as it is compensated for with increases in human-made capital; assumes that human-made capital can substitute for most types of natural capital.

Taking the strong sustainability approach, we would keep separate accounts for human-made and natural capital and ensure that overall natural capital stocks were not depleted. It would be acceptable, for example, to cut down forests in one area only if similar forests were being expanded elsewhere so that the overall forest stock remained constant. Petroleum stocks could be depleted only if alternative energy sources of equal capacity were simultaneously developed. The implementation of strong sustainability would require extensive government intervention in markets and a radical change in the nature of economic activity.

Weak sustainability is easier to achieve. This principle allows for substitutability between natural and human-made capital, provided that the total value of capital is maintained. This may allow us, for example, to cut down forests in order to expand agriculture or industry. It does require, however, that there be an adequate accounting for the *value* of the cleared forest. The forest-clearing activity would not be acceptable unless the value generated in new human-made capital was greater than the value lost.

This principle is closer to standard economic theory. A private owner presumably would make such a calculation and would not willingly exchange a higher-valued resource for a lower-valued one. Government intervention would, however, be required to maintain even weak sustainability when:

- Private owners fail to consider the full ecological value of natural capital (say, a forest products company that considers timber values but is indifferent to endangered species).
- Property rights in natural resources are poorly defined, as is often true in developing countries. This can lead to the rapid plundering of a natural resource base by holders of short-term concessions or illegal users.
- Private property owners have short-term perspectives and fail to consider long-term effects such as cumulative soil erosion.
- Common property resources or public goods are involved.
- Truly irreplaceable resources are at issue, as in the case of species extinction or limited water supplies in arid areas.

Policy Choices and Discounting the Future

The choice between strong and weak sustainability may be difficult. In managing forest resources, for example, strong sustainability may be too restrictive, requiring a country to maintain the same area of forest cover under all circumstances. Weak sustainability, however, places no inherent limits on the amount of forest that can be cut, requiring only a sound economic accounting of its value. Although a middle ground must be defined, this cannot happen simply through the market process. It must be a conscious social choice.

One crucial factor in defining this middle ground is the issue of *discounting the future*. Our discussions of resource allocation over time (Chapter 5) and of cost-benefit analysis (Chapter 7) have highlighted the importance of the discount rate in market choices regarding resource use. In general, the higher the discount rate, the greater the incentive to exploit resources in the present. According to Hotelling's rule, private owners must expect a resource's net price to rise at a rate at least equal to the interest rate before they will conserve that resource for the future. This rarely occurs for most depletable natural resources.

Consider that at a 5 percent discount rate, net resource prices would be expected to double every fourteen years to induce conservation. Otherwise it is more profitable for the owner to extract the resource immediately and invest the proceeds at 5 percent. For renewable resources such as forests, the annual yield must be at least equal to the market rate of interest for private owners to practice sustainable management (see Chapter 19 for a full treatment of this issue). At lower yields, economic incentives favor clear-cutting the forest for immediate monetary gains. In effect, this means treating the renewable resource as a depletable resource and "mining" it out as fast as possible.

The logic of discounting imposes a stiff test on natural resource systems. Unless they can meet a certain yield level, immediate exploitation will take precedence over sustainable management. If major ecological systems and important natural resources fail this test, the resulting rush to exploit resources as fast as possible will make little provision for the future.

Here the strong sustainability principle becomes relevant: Can we trust that a world with much more human-made capital but a severely depleted resource base will meet the needs of the future? Or should we impose a stronger principle of resource conservation to guard our own and future generations' interests?

This is not just a philosophical debate about the long-term future. Many high-quality mineral resources could be largely used up within 30 to 40 years; tropical forests could be virtually eliminated in the same period; ocean and atmospheric systems could be severely degraded; water stored in aquifers could be exhausted and soil erosion could destroy the fertility of millions of acres of cropland within a generation. Applying a strict commercial discounting principle, all this destruction could be seen as quite "rational" and even "optimal."

Ecological economists have argued against using market-based discount rates to guide decisions on long-term resource use. They recommend using a sustainability criterion to promote **intergenerational equity**.[17] In this view, it is wrong to decide issues of long-term investment and conservation in the present simply by applying profit-maximizing criteria. This calls for social judgment regarding conservation of resources for the future.

> **intergenerational equity** the distribution of resources, including human-made and natural capital, across human generations.

Complexity, Irreversibility, and the Precautionary Principle

Another major justification for a sustainability criterion relates to **ecological complexity** and **irreversibility**. Current ecological systems have evolved over many centuries to achieve a balance involving interactions among millions of species of plants and animals, as well as complex physical and chemical relationships in the atmosphere, oceans, and in freshwater and terrestrial ecosystems.

Extensive exploitation of natural resources permanently alters these ecological balances, with effects that are not fully predictable. In some cases, upsetting the ecological balance can lead to disastrous results—desertification, collapse of ocean food systems, depletion and pollution of aquifers, outbreaks of super-pests resistant to insecticides, and the like. Species extinction is a clear example of irreversible damage, imposing unknown economic and ecological costs in the future.

> **ecological complexity** the presence of many different living and nonliving elements in an ecosystem, interacting in complex patterns; ecosystem complexity implies that the impacts of human actions on ecosystems may be unpredictable.
>
> **irreversibility** the concept that some human impacts on the environment may cause damage that cannot be reversed, such as the extinction of species.

Ecological economists, therefore, argue for a **precautionary principle**—we should strive for minimum interference with the operation of natural systems, especially where we cannot predict long-term effects. This principle obviously defies easy definition in economic calculations of resource value and use. Such calculations, therefore, are of value only if we can place them in the broader ecological context, whose priorities must sometimes override market equilibrium logic.[18]

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

first and second laws of thermodynamics physical laws stating that matter and energy cannot be destroyed, only transformed, and that all physical processes lead to a decrease in available energy (an increase in entropy).

entropy a measure of the unavailable energy in a system; according to the second law of thermodynamics entropy increases in all physical processes.

embodied energy the total energy required to produce a good or service, including both direct and indirect uses of energy.

9.5 NERGY AND ENTROPY

As noted above, ecological economics places a special focus on energy. This implies looking to the laws of physics to understand fundamental drivers and limitations on ecosystems and economies. The **first law of thermodynamics** states that matter and energy can be neither created nor destroyed (although matter can be transmuted into energy through nuclear processes). This means that any physical process, including all economic processes, can be seen as a transformation of matter and energy from one form to another. The **second law of thermodynamics** tells us something more about the nature of this transformation. It states that in all physical processes energy is degraded from an *available* to an *unavailable* state.

The formal measure of this process is called **entropy**. Entropy is a measure of the *unavailable* energy in a system, so according to the second law entropy increases as natural processes proceed. The concept of entropy can also be applied to resources other than energy. An easily usable resource, for example a high-grade metal ore, has low entropy. A poorer grade of ore has higher entropy; it can also be used, but only through the application of energy from some other source to refine it.

The best way to understand this rather slippery entropy concept is to think in terms of a specific example, such as burning a lump of coal. In its original state, coal has low entropy—that is, it contains available energy. This energy can be obtained by burning the coal. Once burned, the coal is transformed into ashes and waste heat. The energy can now no longer be used, and the system has moved to a high entropy state.

Nicholas Georgescu-Roegen, a pioneer of ecological economic thought, argued that this law of entropy should be seen as the fundamental governing principle of economics.[19] All economic processes require energy, and transform energy from a usable to an unusable form. The physical outputs of any economic process, thus, can be said to contain **embodied energy**.

For example, an automobile embodies energy used to produce steel and to shape the steel into auto parts, as well as the energy used by workers to assemble it (or the energy used to run assembly-line robots). It also, of course, will require additional fuel energy to run. But eventually all this energy ends up in an unusable form. The fuel energy is dissipated in waste heat and pollution. The car is eventually scrapped and itself becomes waste. In the process, it has provided transportation services to its users, but the net result is the degradation of usable energy and resources into an unusable form.

If we think about the economic process from this perspective, two points become clear. One is that the economic process requires a continual stream of usable energy and resources (low entropy). The other is that it produces a continual stream of waste energy and other waste products (high entropy). Thus the input and output flows of resources and energy to and from the economic system become the fundamental governing mechanisms of production.

This perspective differs dramatically from standard economic theory, in which labor and capital inputs usually rank as the fundamental productive factors. Energy and resource inputs are often not specifically considered and sometimes omitted altogether. Energy and resource prices have no special significance over other input prices, and waste-flow effects, as we have seen, are generally defined as externalities rather than as a central reality of production.

The standard approach works well enough when energy and resources are abundant and cheap and when the environment easily absorbs waste and pollution damage. But as energy and resource demands grow, along with waste and pollution, the entropy perspective emerges as an important factor in understanding the relationship between the economic and ecological systems.

Energy Flows and the Economic Production System

Existing ecological systems are precisely organized for the efficient capture of energy. Millennia of evolution have developed complex and interdependent life systems that draw energy from the environment, using the **solar flux** (flow of sunlight). The fundamental process in all ecosystems is photosynthesis, by which green plants use the sun's energy to produce the organic compounds necessary for life. All animal life is completely dependent on plant photosynthesis, since animals lack the ability to utilize the solar flux directly.

solar flux the continual flow of solar energy to the earth.

Viewed from the perspective of the entropy law, the economic process is essentially an extension of the biological process of using low entropy to support life activity and, at the same time, increasing overall entropy. Industrial systems greatly increase the use rate of entropy. Low-entropy mineral deposits and stored low-entropy in the form of fossil fuels are mined to support the industrial process. Intensive agriculture also "mines" the stored resources of the soil. At the same time, the industrial system greatly increases the emission of high-entropy waste products into the environment.

In standard economic theory, as noted above, there are no inherent limits to growth. But the entropy theory implies that there are limits; economic systems must operate subject to the constraints of:

- Limited stocks of low-entropy resources, in particular high-grade ores and easily available fossil fuels;
- Limited capacity of soils and biological systems to capture solar energy to produce food and other biological resources;
- Limited capacity of the ecosystem to absorb high-entropy waste products.

In some cases, it may be possible to evade specific constraints. For example, we can increase the productivity of soils through adding artificial fertilizers. We cannot evade the entropy law, however, since fertilizer production itself requires energy. In effect, we can expand the limits of the agricultural system by "borrowing" low entropy from somewhere, but only with more rapid use of energy resources (and faster generation of waste and pollution). The one truly "free" source of low entropy is solar energy. Even in the case of solar energy, there are usually material and labor costs involved in capturing and using the available energy.

We can apply the entropy perspective to many different sectors of production: the energy sector itself, agriculture, mining, forestry, fishing, and other industrial sectors. This often gives a different picture of how these economic activities operate. A mining industry, for example, may show increasing productivity over time, measured in standard terms of output relative to labor or capital inputs. But if we concentrate on output per unit of energy inputs, we could well see declining productivity. In other words, we need increasing amounts of energy to achieve the same output as the quality of the mined ore declines.

In this case, we are substituting energy for labor and capital, an economically advantageous choice so long as energy is cheap. However, it means that our economic system becomes more dependent on fossil fuels, which, as we will see in Chapter 11, provide over 80 percent of our industrial energy. Pollution problems associated with fossil fuels also increase. To adapt to planetary entropy limits, we will need to shift to renewable sources of energy, based on the flow of solar energy—either solar power itself, or solar-driven sources such as wind energy.

Ecological economic analysis thus emphasizes the physical basis of production, as opposed to the economic costs of production. This provides a direct link to the physical realities of planetary ecosystems. If we focus only on economic costs, even though we attempt to internalize resource depletion and environmental costs, we may miss the full scope of resource and environmental impacts of economic activity.

9.6 ECOLOGICAL ECONOMICS AND POLICY

We have reviewed the general principles of ecological economics, offering a different and broader perspective on environmental issues. What are some implications of this perspective for economic policy? The ecological values that we have discussed are usually absent from standard market analyses. One way to link standard and ecological analysis at the microeconomic level is to use the concept of **ecosystem services** introduced in Chapter 6. Valuation of ecosystem services, while not necessarily reflecting all ecological functions, can provide a way to introduce these functions into economic markets—specifically, to set up systems that require users to pay for ecosystem services, creating an incentive to maintain and restore such services. At the macroeconomic level, an ecological perspective implies strong policies on climate, energy, biodiversity, water and oceans, and numerous other areas in which the human economy interacts with the environment.

> **ecosystem services** beneficial services provided freely by nature such as flood protection, water purification, and soil formation.

Payments for Ecosystem Services

Managers of natural resources typically face market incentives that provide financial rewards for exploitation. For example, owners of forest lands have a market incentive to cut down trees rather than manage the forest for carbon sequestration, wildlife habitat, flood protection, and other ecosystem services. These services provide the owner with no financial benefits, and thus are unlikely to sway management decisions. But the economic benefits provided by these services, based on their non-market values, may exceed the economic value of the timber. For example, a United Nations initiative has estimated that the economic benefits of ecosystem services provided by tropical forests, including climate regulation, water purification, and erosion prevention, are over three times greater per hectare than the market benefits.[20] Thus cutting down the trees is economically inefficient, and markets are not sending the correct "signal" to favor ecosystem services over extractive uses.

One solution to this inefficiency is to change market incentives so that preservation of ecosystems services becomes financially attractive to resource owners. This approach is known as **payments for ecosystem services (PES)**. PES systems provide incentives for resource owners to maintain or enhance ecosystem services. These incentives are normally monetary payments in exchange for the provision of various ecosystem services.

payments for ecosystem services (PES) the provision of economic incentives for resource owners to maintain or enhance ecosystem services.

In addition to encouraging the preservation of forest ecosystems, PES programs have been established that preserve watershed quality, biodiversity, and scenic beauty. For example, a joint PES project by The Nature Conservancy and the Ecuadorian government aims to protect the water supply to Quito (the capital of Ecuador) by paying land owners in the watershed to implement improved agricultural practices.[21] In a PES scheme in Bolivia to protect and improve water quality, small-scale farmers are encouraged to convert degraded agricultural land to other uses by free distribution of beehives and fruit trees.[22]

In order for a PES program to be successful at improving environmental quality, it should meet the following four criteria:[23]

conditionality a requirement of a successful PES program; the payments must be conditional upon a resource owner implementing changes that actually improve environmental outcomes.

additionality a requirement of a successful PES program; the environmental benefits must be in addition to what would have occurred without the payments.

leakage a requirement of a successful PES program is avoiding leakage; the environmentally-beneficial actions a resource owner takes must not be offset by other changes that are environmentally detrimental.

permanence a requirement of a successful PES program; the environmental benefits must persist for the long-term.

1. The payments must be conditional upon the resource owner implementing changes that actually improve environmental outcomes. This conditionality criterion requires that a system is in place to verify that the resource owner does what is agreed upon, such as planting trees or implementing sustainable agriculture practices.
2. The actions the resource owner agrees to take must display additionality. This means that the environmental benefits would not have been obtained without the payments. For example, suppose a landowner had no plans to cut down trees on his property. Paying this landowner to simply do what he already planned would not provide an additional environmental benefit.
3. The environmental benefits must not suffer from leakage. This means that the beneficial actions a resource owner takes are not offset by other changes. For example, suppose a landowner receives payments to preserve trees on a 20-hectare parcel that would have otherwise been cut for timber. In isolation, this would meet the additionality criterion. But if the landowner then decides to cut trees on another 20-hectare parcel that would otherwise not have been cut, leakage occurs and the payments produce no net environmental benefits.
4. Finally, a PES program must demonstrate permanence. This simply means that the environmental benefits should persist for the long-term. If landowners receive annual payments to preserve forest lands, but then cut down the trees once the payments stop (thus releasing their stored carbon into the atmosphere), the program produces no permanent benefits.

In addition to providing environmental benefits, PES programs are often advocated as a means to reduce poverty in developing countries. The expectation is that resource owners will only participate in voluntary PES programs if they increase their incomes, potentially lifting them out of poverty. But the linkages between PES programs and poverty are often more complex.[24] One problem is that the world's poorest people are often not owners of natural resources and are thus unable to receive payments in a PES program. Even when poor people do have secure ownership of land and natural resources, they may not own enough to make the PES programs worthwhile.

For example, in a PES program in Vietnam that provided payments on a per-hectare basis for forest preservation, the average small landowner only possessed two hectares. The PES payments were not sufficient to justify the transaction costs of applying for the program, and most of the payments went to larger, wealthier landowners.[25] Other barriers to participation may exist such as requirements that complex forms be completed, or that applicants file paperwork in distant locations.

There may also be negative indirect effects of PES programs on poor people. Low-income workers may lose their jobs if a PES program encourages conversion of agricultural land to protected areas. Subsistence hunter/gatherers may lose access to traditional areas as a result of PES programs. "There is reason to worry that the truly poor may find themselves unable to participate as suppliers of ecosystem services, displaced from their jobs, and cut off from natural resources that they previously exploited (either sustainably or otherwise)." [26] One illustration of an unexpected indirect effect was a PES program in Bolivia that successfully eliminated destructive logging. Once logging stopped the local roads were no longer maintained and small communities in the area were faced with higher transportation costs.[27]

PES programs have clearly produced significant environmental benefits in many cases—see Box 9.1 for one example. But to what extent PES programs have the potential to reduce poverty requires further study.

Box 9.1
PAYMENTS FOR ECOSYSTEM SERVICES IN UGANDA

A number of research studies in recent years have sought to document the quantitative environmental impact of PES programs. One such study, published in 2016, set up a randomized control trial (RCT) in Uganda to measure the impact of a PES program designed to reduce deforestation. (An RCT compares participants in a particular program with a similar group not in the program).

Farmers in the program received approximately US$30 per hectare per year for refraining from clearing forest lands. A total of 60 villages in western Uganda were randomly selected to participate in the PES program, while another 61 villages were selected to be the control group.

The researchers then used high-resolution satellite imagery to measure tree cover in the treatment and control villages. The results indicated that the PES program did reduce deforestation. Tree cover declined by 7–10 percent in the control villages, while it only decreased 2–5 percent in the treatment villages. The satellite data also revealed that leakage was not occurring by studying tree cover in forest lands around each village.

Only 32 percent of eligible participants in the treatment villages signed up for the PES program. Follow-up surveys determined that the low participation rate was attributed to insufficient marketing of the program and a concern among some landowners that the program was a scheme to take over their land. Of those who participated, 80 percent met the conditions of the PES contract. However, as the study only lasted two years the researchers suggested that deforestation rates could eventually return to baseline levels without further interventions.

Source: Jayachandra *et al.*, 2016.

Ecological Macroeconomics

An ecological perspective suggests that overall human impact on the planet is so great that it requires a fundamental change in economic systems to avoid an "overshoot-collapse" syndrome, as described in the basic limits-to-growth model discussed in Chapter 2. Some scientists and ecological economists have called for recognition of the current era as the "Anthropocene"—meaning a period in which human activities have become the dominant global force shaping Earth's climate and ecosystems.[28] In this period, an ecological economics approach suggests macro-level changes in:

- Energy systems, adopting renewable energy to prevent catastrophic climate change
- Agricultural systems, to promote long-term sustainability
- Population growth, which needs to stabilize to avoid ever-increasing human demands on the biosphere
- Nonrenewable resource use, to conserve resources for the future
- Renewable resources, to prevent over-use and preserve the integrity of water cycles, forests and fisheries, and conserve biodiversity

In each of these areas, standard economic analysis can provide some policy insights, but it will be important also to take a broader ecological perspective to understand the overall relationship between economic activities and the natural systems that support them. As we explore these topics in Chapters 10–20, we will draw on both standard and ecological perspectives as we seek to analyze each topic area and discuss policy perspectives.

Summary

Ecological economics takes a different approach from standard environmental economic analysis based on markets. It emphasizes the dependence of the human economy on natural ecosystems and gives special emphasis to the concept of natural capital. While much of standard economics is concerned with the accumulation and productivity of human-made capital, ecological economics focuses on the maintenance of the natural capital systems that support life and economic activity. Natural capital includes all the natural resources, oceans, atmosphere, and ecosystems of the planet. These must be accounted for and should be managed according to sustainable principles, so that their functions are not degraded over time.

In this perspective, economic systems cannot grow without limit but must achieve a sustainable scale for economic activity at which the planet's ecosystems are not subjected to undue stress. Significant evidence indicates that current economic activity exceeds these limits or badly strains them. One measure of this is the proportion of photosynthetic energy appropriated for human use, now about 25 percent of photosynthesis, with much higher proportions in agricultural and densely populated areas. Significant further growth in human demand would thus leave little room for other living systems of the earth.

The concept of sustainability, although important to managing natural capital, is difficult to define. A "weak" definition relies on the possibility of replacing natural ecosystem functions with human-made substitutes. A "strong" definition assumes that humans have limited