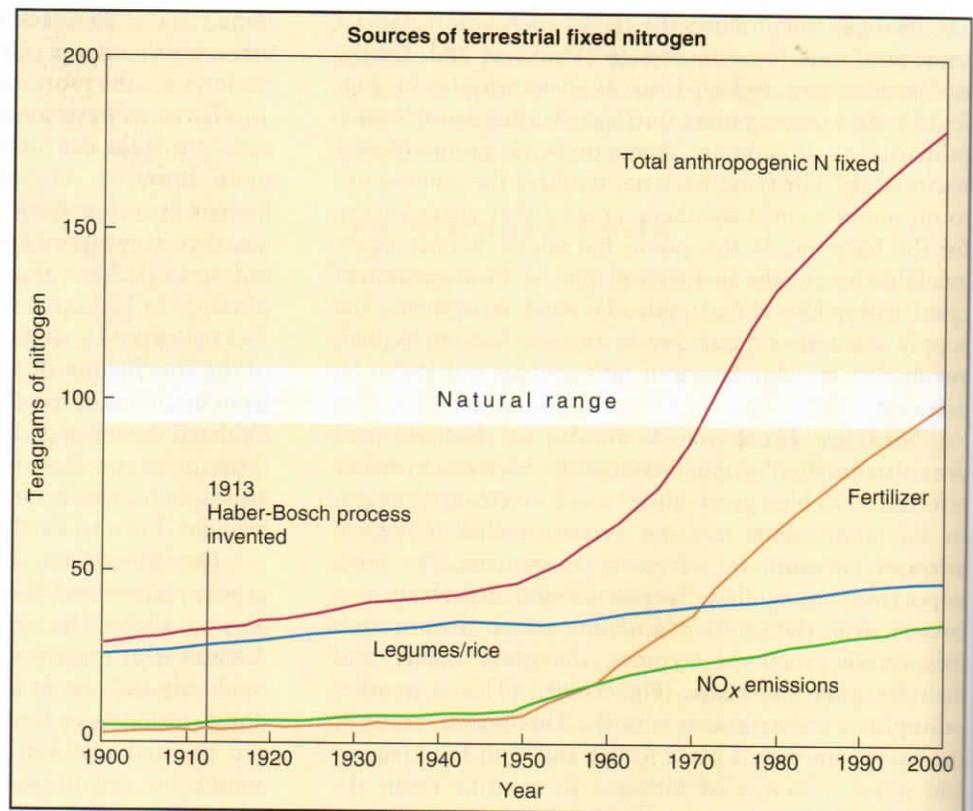


**Figure 3–21 Terrestrial fixed nitrogen.** Nitrogen fixed by human-promoted (anthropogenic) processes have surpassed the natural levels of nitrogen fixation, essentially fertilizing the global ecosystem.



beans, soybeans, alfalfa), so they draw nitrogen from the air, thus increasing the normal rate of nitrogen fixation on land. Crops that are nonleguminous (corn, wheat, potatoes, cotton, and so on) are heavily fertilized with nitrogen derived from industrial fixation. Also, fossil-fuel combustion fixes nitrogen from the air. All told, these processes add some 150 teragrams of nitrogen to terrestrial ecosystems annually (Fig. 3–21). This is approximately 1.5 times the natural rate of nitrogen fixation. In effect, we are more than doubling the rate at which nitrogen is moved from the atmosphere to the land.

The consequences of this global nitrogen fertilization are serious. Acid deposition has destroyed thousands of lakes and ponds and caused extensive damage to forests (Chapter 21). The surplus nitrogen has led to “nitrogen saturation” of many natural areas, whereby the nitrogen can no longer be incorporated into living matter and is released into the soil. There, it leaches cations (positively charged mineral ions) such as calcium and magnesium from the soil, which leads to mineral deficiencies in trees and other vegetation. Washed into surface waters, the nitrogen makes its way to estuaries and coastal oceans, where it promotes rich “blooms” of algae, some of which are toxic to fish and shellfish. When the algal blooms die, they sink to deeper water or sediments, where they reduce the oxygen supply and kill bottom-dwelling organisms like crabs, oysters, and clams, creating “dead zones.” (See Chapter 17.) Of course, these are just the observable effects of nitrogen enrichment; there may be other effects that

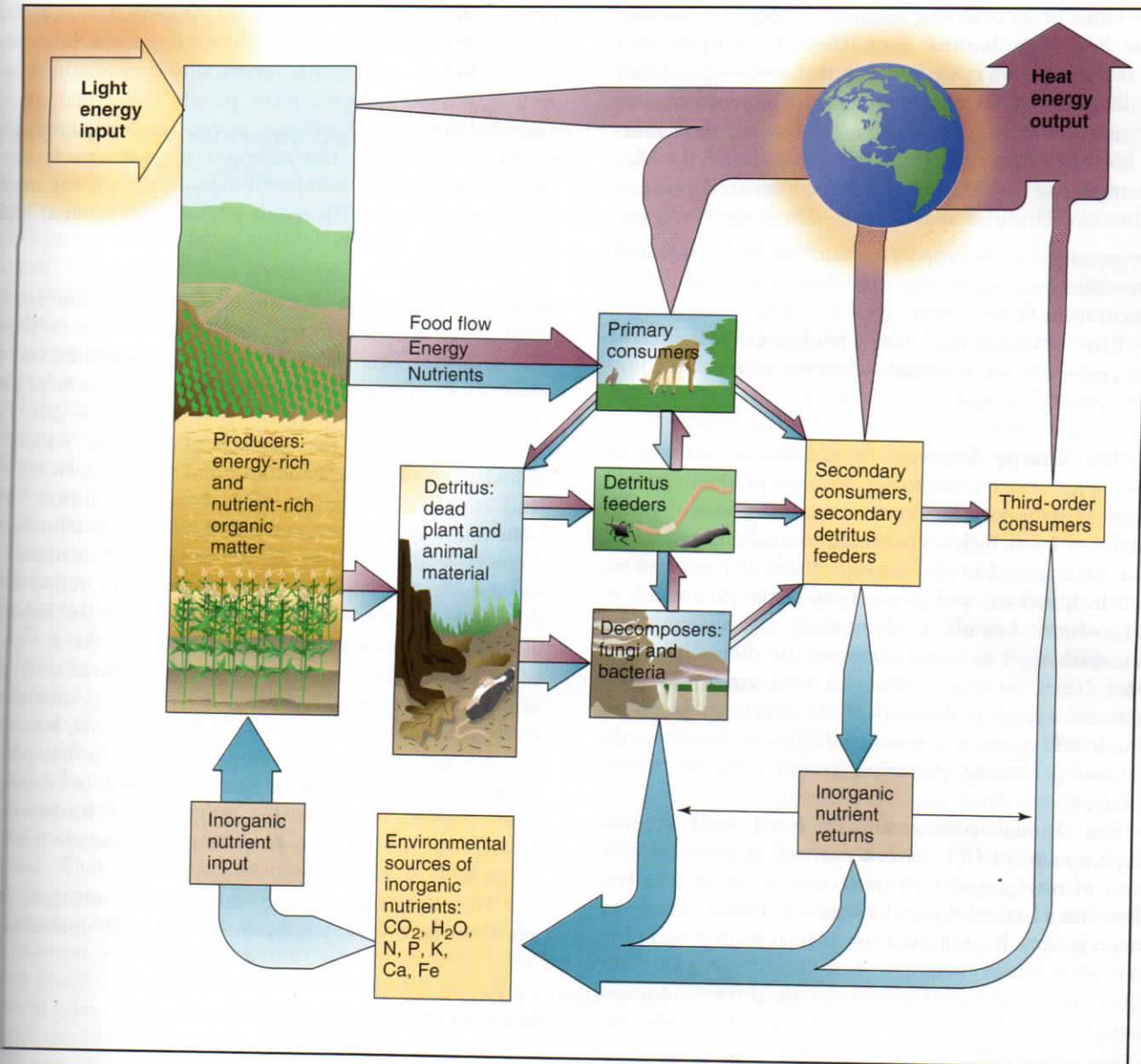
have not yet been well documented, such as a loss of biodiversity by encouraging luxuriant growth of a few dominant plant species.

Although we have focused on the cycles of carbon, phosphorus, and nitrogen, cycles exist for oxygen, hydrogen, and all the other elements that play a role in living things. Also, while the routes taken by distinct elements may differ, all of the cycles are going on simultaneously, and all come together in the tissues of living things. As the elements cycle through ecosystems, energy flows in from the Sun and through the living members of the ecosystems. The links between these two fundamental processes of ecosystem function are shown in Fig. 3–22.

### 3.4 Implications for Human Societies

#### Ecosystem Sustainability

Ecosystems have existed for thousands of years or more, maintaining natural populations of the biota and the processes that they carry out, processes that in turn sustain the ecosystems. In this chapter, we have focused on energy flow and nutrient cycling—how natural ecosystems work, in *theory*. In *reality*, however, it is the Earth’s specific ecosystems that we depend on for goods and services (ecosystem capital). Is our use of natural and managed ecosystems a serious threat to their long-term sustainability? We will look briefly at how we are affecting energy flow and nutrient cycling, but a more detailed



**Figure 3–22** Nutrient recycling and energy flow through an ecosystem. Arranging organisms by feeding relationships and depicting the energy and nutrient inputs and outputs of each relationship shows a continuous recycling of nutrients (blue) in the ecosystem, a continuous flow of energy through it (red), and a decrease in biomass in it (thickness of arrows).

investigation of our use of specific types of ecosystems must wait until Chapter 11.

One of the reasons for studying natural ecosystems is that they are models of sustainability. As a result, we might benefit from understanding what it is that makes them sustainable and, where possible, how to emulate them. As Figure 3–22 shows, it is the Sun that energizes the processes of energy flow and nutrient cycling, and the biological, geological, and chemical interactions within and between ecosystems are the drivers of change. The key to their sustainability, therefore, is that ecosystems use sunlight as their source of energy.

**Significance of Energy Flow.** Humans make heavy use of the energy that starts with sunlight and flows through natural and agricultural ecosystems. Agriculture,

for example, provides most of our food. To accomplish this, we have converted almost 11% of Earth's land area from forest and grassland biomes to agricultural ecosystems. Grasslands provide animals for labor, meat, wool, leather, and milk. Forest biomes provide us with 3.3 billion cubic meters of wood annually for fuel, building material, and paper. Finally, some 15% of the world's energy consumption is derived directly from plant material.

Calculations of the total annual global net primary production of land ecosystems average out at 120 petagrams of dry matter, including agricultural as well as the more natural ecosystems. Two independent groups of researchers have calculated that humans currently appropriate 32% of this total production for agriculture, grazing, forestry, and human-occupied lands. Although

these kinds of calculations require making a lot of estimates based on limited data, they do indicate that humans are using a large fraction of the whole, and that it is likely to grow. Further, because humans convert many natural and agricultural lands to urban and suburban housing, highways, dumps, factories, and the like, we cancel out an additional 8% of potential primary production. Thus, we appropriate 40% of the land's primary production to support human needs. In so doing, we have become the dominant biological force on Earth. As ecologist Stuart Pimm puts it, "Man eats Planet! Two-fifths already gone." Is this level of use sustainable? If so, and if our use increases, when do we reach the limits of sustainable use?

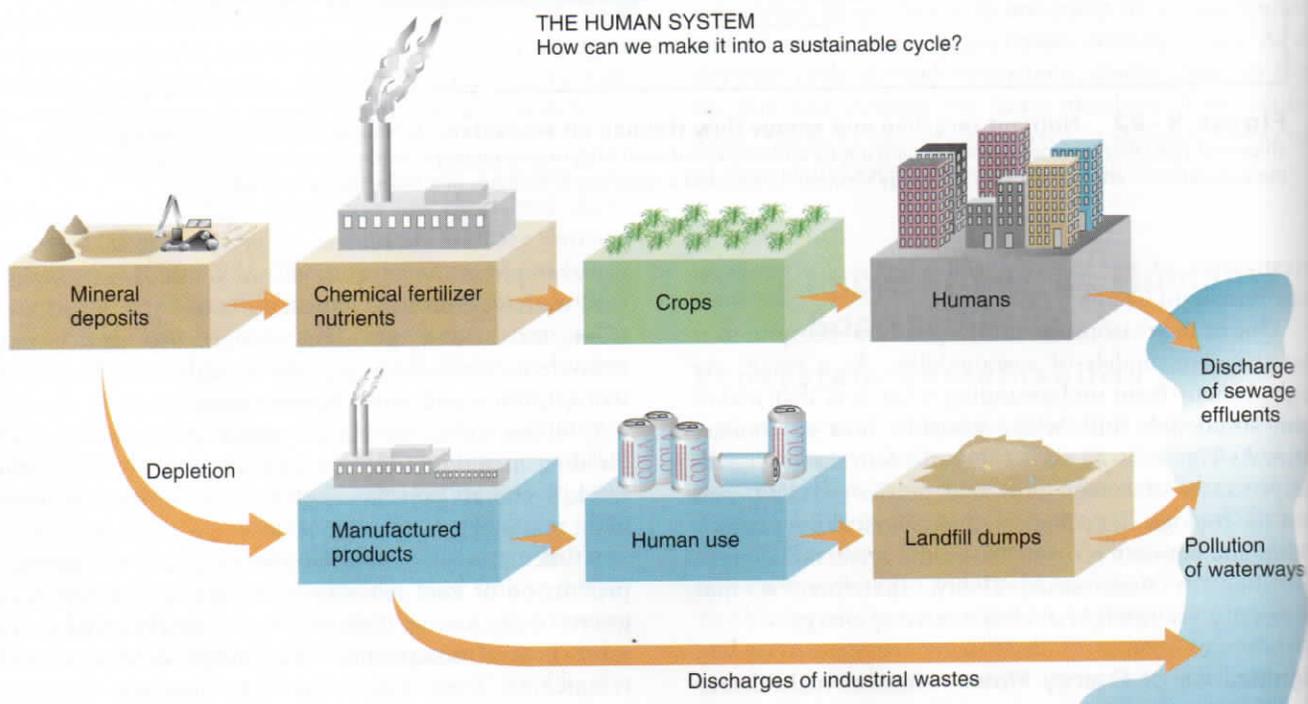
**Another Energy Source.** In addition to running on solar energy, which creates the ecosystem productivity that humans appropriate, the current human system depends heavily on fossil fuels—coal, natural gas, and crude oil. Crude oil is refined to produce liquid fuels such as gasoline, diesel fuel, fuel oil, and so on. Even in the production of food, which depends fundamentally on sunlight and photosynthesis, it is estimated that we use about 10 calories of fossil fuel for every calorie of food consumed. This additional energy is depleted in the course of preparing fields, fertilizing the plants, controlling pests, harvesting the food, and processing, preserving, transporting and, finally, cooking it.

The annual combustion of fossil fuels releases 6.6 petagrams of  $\text{CO}_2$  carbon, as well as some 35 teragrams of nitrogen and 50 teragrams of sulfur. The biosphere has a limited capacity to absorb these by-products, however, so air pollution problems result, including

urban smog, acid rain, and the potential for global climate change. Also, problems stemming from the depletion of fuels—particularly, crude oil—are on the horizon. For these reasons, most people concerned about sustainability are solar-energy advocates. Solar energy is extremely abundant. Just as important, we already have the technology to obtain much more of our energy needs from sunlight and the forces it causes, such as wind. (See Chapter 14.)

**Sustainability and Nutrient Cycling.** *Ecosystems dispose of wastes and replenish nutrients by recycling the elements.* This maintains their sustainability, indefinitely. Human systems, by contrast, are based in large part on a *one-directional flow* of elements (Fig. 3–23). For example, the fertilizer–nutrient phosphate, which is mined from deposits, ends up going into waterways via land runoff and effluents from sewage treatment. The same one-way flow occurs with such metals as aluminum, mercury, lead, and cadmium, which are the “nutrients” of our industry. At one end, these resources are mined from the Earth; at the other, they end up in dumps and landfills as items containing them are discarded. As a result, there are depletion problems at the resource end and pollution problems at the other. The Earth has substantial (but not unlimited) deposits of most minerals; however, the capacity of ecosystems (even the whole biosphere) to absorb wastes without being disturbed is comparatively limited. This limitation is aggravated, furthermore, by the fact that many of the products we use are nonbiodegradable.

Human intrusion into the carbon, nitrogen, and phosphorus cycles is substantial and will undoubtedly



**Figure 3–23** One-directional nutrient flow in human society.