CHAPTER

5

Abiotic Resources

In this chapter, we closely examine the five **abiotic resources** introduced in Chapter 4: fossil fuels, minerals, water, land, and solar energy. Our goal is to explain how the laws of thermodynamics, the distinction between stock-flow and fund-service resources, and the concepts of excludability and rivalness relate to these resources, in order to better understand the role they play in the ecological-economic system. We will also assess the extent to which substitutes are available, and the degree of uncertainty associated with each resource. As we will see, however, abiotic resources are fundamentally different from each other, and it is their even greater dissimilarity from biotic resources that binds them together, more than their similarity to each other. Perhaps the most important distinction is that biotic resources are simultaneously stock-flow and fund-service resources that are self-renewing, but human activities can affect their capacity to renew. Abiotic resources are either nonrenewable (fossil fuels) or virtually indestructible (everything else).

The differences between abiotic resources probably deserve more emphasis than their similarities, and we'll start with a brief summary. Fossil fuels and mineral resources are frequently grouped together under the classification of nonrenewables. The laws of thermodynamics, however, force us to pay attention to an important difference: The energy in fossil fuels cannot be recycled, while mineral resources can be, at least partially. Water is one of the most difficult resources to categorize, precisely because it has so many different forms and uses. Fossil aquifers (those that are not being recharged) are in some ways similar to mineral resources—once used, the water does not return to the ground, and while it cannot be destroyed, it can become less useful when polluted by chemicals, nutrients, or salt. Rivers, lakes, and streams, in contrast, share similarities with biotic resources: They are renewable through the hydrological cycle driven by solar energy, and they can exhibit stock-flow and fund-service properties simultaneously. However, human activity cannot affect the total stock of water to any meaningful extent, while we can and do irreversibly destroy biotic resources. Similarly, land as a physical substrate, a location (hereafter referred to as Ricardian land) cannot be produced or destroyed in significant amounts by human activity (with the exception of sea level rise induced by anthropogenic climate change), and solar energy flows are not meaningfully affected by humans at all—though we can affect the amount of solar energy that moves in and out of the atmosphere. We now examine these resources in more detail.

FOSSIL FUELS

Perhaps the simplest resource to analyze is **fossil fuels**, or hydrocarbons, upon which our economy so dramatically depends. In 1995, crude oil supplied 38% of energy inputs into the global economy, followed by coal at 25% and natural gas at 22%. In all, 85% of the energy in the economy comes from fossil hydrocarbons.[1] In geological terms and as far as humans are concerned, fossil fuels are a fixed stock. For a variety of reasons, however, it is extremely difficult to say precisely how large that stock is.

For practical purposes, we are only concerned with recoverable supplies. But what does recoverable mean? Clearly, hydrocarbons are found in deposits of varying quality, depth, and accessibility, and there are different costs associated with the extraction of different deposits. In economic terms, we can define recoverable supplies as those for which total extraction costs are less than the sales revenues. However, fossil fuel prices fluctuate wildly, and recoverable supplies defined in this way show similarly chaotic variation through time. We could also define recoverable supplies in entropic terms, in which case a hydrocarbon is recoverable if there is a net energy gain from extraction; that is, it takes less than a barrel of oil to recover a barrel of oil. This measure must include all the energy costs, including those of exploration, machinery, transportation, decommissioning, and so on. While technological change can reduce these, there is a certain irreducible limit to the energy costs of extracting fossil fuels. It takes 9.8 joules of energy to lift 1 kilogram 1 meter, and no amount of technology can change that basic fact.

As we deplete the most accessible hydrocarbon supplies first, over time it will take more and more energy to recover remaining supplies. In other words, the *energy return on investment*, which is "the ratio of gross fuel extracted to economic energy required directly and indirectly to deliver the

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[1] J. Edwards, *AAPG Bulletin* 81(8), August 1997, American Association of Petroleum Geologists.

fuel to society in a useful form," declines over time.[2] In entropic terms, the energy cost of oil and natural gas extraction in the United States increased by 40% from 1970 to the 1990s.[3] During the 1950s in the U.S., every barrel of oil invested in exploration led to the discovery of about 50 more. By 1999, the ratio was about one to five. Some experts predict that by the year 2005, the ratio will be one to one, and no matter what the price of oil, it will make no sense to search for more in the U.S.[4] Still, under either the economic or the entropic definition of *recoverable*, estimates of recoverable reserves change constantly. Largely this is the result of new discoveries, but it also results from dramatically different methods for calculating "proven" supplies between different companies and different countries, with frequent changes often based on political or economic motives.[5] Petroleum geologists can, however, assign reasonable probabilities to different estimates of total stocks.

BOX 5-1 ESTIMATING OIL STOCKS

Every year, the world consumes in the neighborhood of 25 billion barrels of oil (Gbo). Yet at the end of most years, reported reserves of oil are greater than they were at the start, and there is a fairly wide range of estimates as to what those reserves actually are. The increase is possible as long as new oil discoveries are greater than oil consumed, but that is rarely the case anymore. For example, in 1997, the world used about 23 Gbo and discovered 7 Gbo, yet estimated reserves *increased* by 11 Gbo. How do we explain this anomaly?

When geologists estimate the quantity of oil in any given field, they assign a probability to the estimate. For example, in the late 1990s, geologists estimated that the Oseberg field in Norway would supply 700 million barrels of oil with 90% certainty (known as probability 90, or P90) and 2500 with 10% certainty (known as P10). Different corporations and countries generally use some number within the P10–P90 range when

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[2] C. Cleveland, R. Costanza, C. Hall, and R. Kaufmann, Energy and the US Economy: A Biophysical Perspective, *Science* 225: 297 (1984).

[3] C. Cleveland and D. Stern, "Natural Resource Scarcity Indicators: An Ecological Economic Synthesis." In C. Cleveland, D. Stern, and R. Costanza, eds., *The Economics of Nature and the Nature of Economics*. Cheltenam, England: Edward Elgar, 2001.

[4] J. Hanson, Energetic Limits to Growth, *Energy* (Spring 1999). Online: http://www.dieoff.com/page175.htm. This does not mean that perverse economic incentives cannot lead to oil being recovered beyond the 1:1 ratio. During the 1970s, in an effort to decrease dependence on imported oil, the U.S. government offered preferential prices for domestic oil. This meant that cheaper imported oil could be used to extract more expensive domestic oil, and domestic producers could profit even when it took more than one barrel of oil to extract a barrel.

[5] C. J. Campbell and J. H. Laherrère, The End of Cheap Oil, *Scientific American*, March 1998.

stating their reserves, and they are often purposefully vague about what number they use. Higher reported reserves can increase stock prices, provide greater access to credit, and for OPEC countries, increase their quotas. As oil fields are exploited, geologists can use the information acquired to make better estimates about how much they contain. Based on this information and other factors (e.g., moving from P90 to P50 estimates), countries frequently revise their reserve estimates from existing fields, and often upward. In the absence of major new discoveries or technological breakthroughs in the late 1980s, six OPEC countries alone revised their estimates upward by 287 Gbo, 40% more than all the oil ever discovered in the U.S.!

When calculating global oil reserves, it makes most sense to sum the P50 estimates across countries, but even this is no easy task. In addition, revised estimates from existing reserves are not new discoveries and should not be counted as such.[a]

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[a] *C. J. Campbell and J. H. Laherrère,* The End of Cheap Oil, *Scientific American (March 1998).*

THINK ABOUT IT!

Economists argue that price reflects scarcity. Do you think the price of oil is a good indicator of how much oil is left in the ground? Why or why not?

Regardless of what the stocks of fossil fuels are, however, they are stocks that can be extracted as flows, and the rate of flow is largely determined by human efforts. If we had adequate infrastructure, we could theoretically extract all entropically recoverable fossil energy stocks in a single year, or we could make them last 1000 generations. How long recoverable stocks will last, therefore, is determined as much by how fast we extract them as by how much there actually is. We almost certainly will never exhaust fossil fuel stocks in physical terms, because there will always remain some stocks that are too energy-intensive or too expensive to recover. From this point of view, fossil fuel stocks are nonrenewable but not exhaustible.

As we extract fossil fuels, we will logically extract them from the most accessible and highest-quality known reserves first, where net energy gains are highest.[6] These stocks essentially offer the lowest-entropy resource. Therefore, as we continue to extract fossil fuels over time, we can expect not only a *quantitative* decrease but also a *qualitative* decline in stocks. For example, the first oil to be extracted actually pooled on the surface and erupted in geysers from wells with no pumping. But as

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[6] Note that the largest and most accessible reserves are also the most likely to be discovered first.

stocks diminish, it takes more and more energy to extract energy; ever-larger fractions of a barrel of oil are required as energy inputs to retrieve a barrel of oil as output, until we have reached entropic exhaustion. (As mentioned earlier, we are probably very near this point already in the U.S.)

Of course, resource exhaustion is only one component of fossil fuel use. Used fuel does not disappear; it must return to the ecosystem as waste. Acid rain, global warming, carbon monoxide, heat pollution, and oil spills are unavoidably associated with the use of fossil fuels. On a small scale, some of these wastes could be readily processed by natural systems, but on the current scale, they pose serious threats. Indeed, the growing accumulation of waste products from fossil fuel use and the negative impacts these have on planetary ecosystems is probably a far more imminent threat to human welfare than depletion; the sink will be full before the source is empty.

We must reiterate here that ecosystems (as shorthand for the primary producers they sustain) themselves capture solar energy, and humans make direct use of much of the energy they capture. If waste products from fossil fuel use diminish the ability of these ecosystems to capture energy, there are more energy costs to fossil fuel extraction than the direct ones discussed above. These costs are, however, several degrees of magnitude more difficult to measure—and therefore that much more likely to be ignored (Figure 5.1).

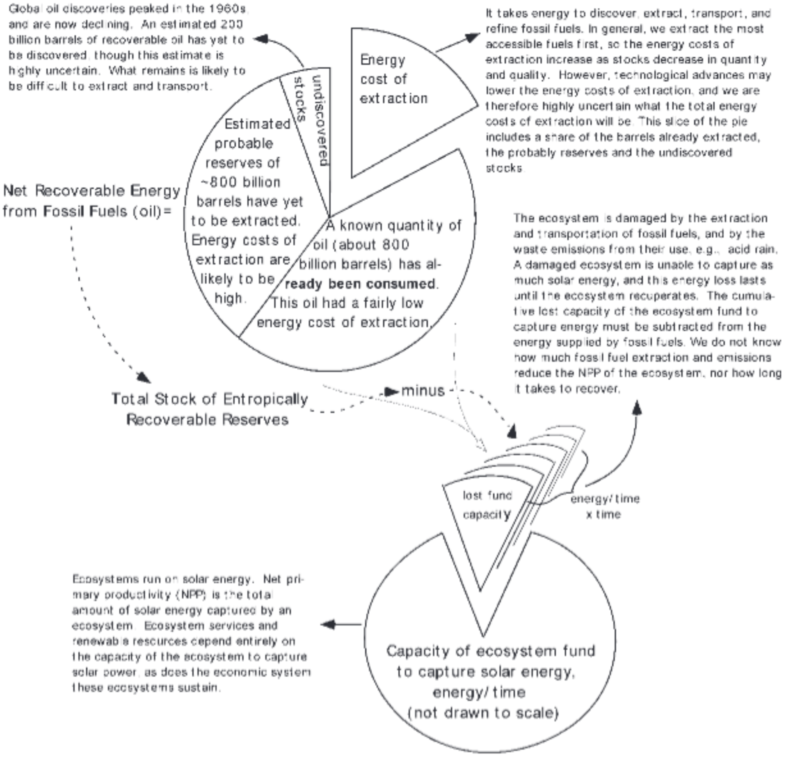
THINK ABOUT IT!

Many people are concerned by the United States' dependence on oil imports from a number of politically unstable regions and countries (e.g., the Middle East, Nigeria, Venezuela, Colombia). Proposed solutions to this problem have included increased domestic drilling and extraction, greater energy efficiency, and the development of renewable energy sources. What do you think are the pros and cons of each approach?

The basic equation here is:

net recoverable energy from oil = (initial total stock of entropically
recoverable reserves) – (energy cost of extraction) –
(loss of solar energy due to induced loss of capacity to capture)

To obtain net recoverable energy remaining in fossil fuel stocks, we also would need to subtract oil already consumed. Net energy from fossil fuels must account for the damage fossil fuel use causes to the ability of the sustaining system to capture solar energy, a fund-service resource. This lost capacity is measured as energy-flow/time, and we must account for the



Global oil discoveries peaked in the 1960s, and are now declining. An estimated 200 billion barrels of recoverable oil has yet to be discovered, though this estimate is highly uncertain. What remains is likely to be difficult to extract and transport.

It takes energy to discover, extract, transport, and refine fossil fuels. In general, we extract the most accessible fuels first, so the energy costs of extraction increase as stocks decrease in quantity and quality. However, technological advances may lower the energy costs of extraction, and we are therefore highly uncertain what the total energy costs of extraction will be. This slice of the pie includes a share of the barrels already extracted, the probably reserves and the undiscovered stocks.

The ecosystem is damaged by the extraction and transportation of fossil fuels, and by the waste emissions from their use, e.g., acid rain. A damaged ecosystem is unable to capture as much solar energy, and this energy loss lasts until the ecosystem recuperates. The cumulative lost capacity of the ecosystem fund to capture energy must be subtracted from the energy supplied by fossil fuels. We do not know how much fossil fuel extraction and emissions reduce the NPP of the ecosystem, nor how long it takes to recover.

Ecosystems run on solar energy. Net primary productivity (NPP) is the total amount of solar energy captured by an ecosystem. Ecosystem services and renewable resources depend entirely on the capacity of the ecosystem to capture solar power, as does the economic system these ecosystems sustain.

Figure 5.1 • Net recoverable energy from fossil fuels.

total amount of energy not captured from the time the damage occurs to the time the fund-service recovers.[7]

What points can we draw from this discussion of fossil fuels? First, once fossil fuels are used, they are gone forever—they are rival goods. While a seemingly trivial point, this has important implications for economic policy, as we will show in Chapter 11. Second, while fossil fuel stocks are finite, they are a stock-flow resource that can be extracted virtually as quickly as we wish, limited only by existing infrastructure, knowledge of stock locations, and the energy costs of extraction. We have control of the spigot and have been opening it a bit wider every decade. Eventually the reservoir must run dry. This is in stark contrast to flows of solar energy, as we pointed out in Chapter 4.

Third, our current populations and economic systems depend for survival on the use of fossil fuels. Fossil fuels not only supply 85% of our en-

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[7] Estimates of oil already consumed, probable reserves, and oil yet to be discovered are from Campbell and Laherrère, ibid.

ergy needs, much of which is used to produce food; they also provide the raw materials for a substantial portion of our economic production, including ubiquitous plastics and, even more importantly, the fertilizers, herbicides, and pesticides that help provide food for 6 billion people. At this point, we do not have the technologies available to support 6 billion people in the absence of fossil fuels.

While we may be able to substitute renewable energy for fossil fuels, it is highly uncertain that we can do so before the negative impacts of their waste products force us to stop using them or the fuels themselves are depleted.

THINK ABOUT IT!

The U.S. and Canada have vast deposits of shale oil and tar sands, respectively. Both of these are fossil fuels, but of fairly low quality, requiring more energy to extract and process than conventional fossil fuels, and creating more associated waste. Do you think these resources present possible solutions to our energy problems? You may need to do some quick research on the Internet. Can you find any information on their energy returns to investment and waste outputs?

MINERAL RESOURCES

Though typically grouped together with fossil fuels in economics textbooks and labeled nonrenewable resources, minerals differ in important respects from fossil fuels. Like fuels, nonenergy minerals can be analyzed in terms of stocks and flows. We know the total stock is finite, and according to the First Law of Thermodynamics, this imposes a physical limit on their contribution to the material growth of the economy. Again, technology can increase the efficiency with which we extract minerals from ore, but there exists an entropic limit to efficiency. Valuable mineral deposits occur in varying degrees of purity, and, like fuels, the degree of purity can be looked at as a measure of low entropy. Highly concentrated ores are highly ordered low entropy.[8] It is much easier to extract their mineral content, and they are much more valuable. As our growing economy depletes these most valuable ores first, we must move on to ores of lower and lower purity, incurring higher and higher processing costs.

As in the case of oil, we are not exactly certain of the total stock of any particular mineral, but geologists assign reasonable probabilities to different estimates. Even the most efficient process conceivable will require

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[8] Even if we do not accept the notion of entropy in materials, concentrated ores require much less low-entropy energy to process.

some energy to extract minerals from an ore, and the less pure the ore, the more energy that will be required. Currently, mining accounts for about 10% of global energy use.[9] However, unlike fossil fuels that cannot be burned twice, materials can be recycled (though this, too, requires energy). Therefore, we must think in terms of nonrenewable subterranean stocks as well as aboveground stocks, which accumulate as the subterranean ones are depleted. Still, we cannot avoid the laws of entropy even here, and use leads to dissipation through chemical and physical erosion; therefore, 100% recycling of any material may be impossible.

There is considerable debate over the impossibility of 100% recycling, as well as the implications. Georgescu-Roegen argues that because solar energy can provide a substitute for fossil fuels and nothing can provide a substitute for minerals, mineral depletion is actually more of a concern than fossil fuel depletion, and its inevitability means that a steady-state economy[10] is impossible (see Box 3.2). In contrast, Ayres claims that even if all elements in the Earth's crust were homogeneously distributed (the material equivalent of "heat death" mentioned above), a sufficiently efficient solar-powered extraction machine would enable us to extract these elements,[11] presumably at a rate that would provide enough raw materials to maintain the machine and still leave a material surplus. This scenario implicitly assumes that damage caused by extracting all the resources from the Earth's crust in the first place, and their consequent return to the ecosystem as waste, would not irreparably damage the Earth's ability to capture solar energy and sustain life.

Alternatively, we may be able to master the art of creating polymers from atmospheric CO_2, which could provide substitutes for many of the minerals we currently use. If such polymers were biodegradable and simply returned to the atmosphere as CO_2 we would presumably be able to achieve 100% recycling (though in this case we may not want to, at least not before atmospheric CO_2 stabilizes at preindustrial levels). Of course, none of these propositions can currently be proven empirically. Nonetheless, it appears that mineral deposits are sufficiently large, and recycling has the potential to become sufficiently efficient, that with careful use, minimizing waste and appropriate substitution where possible, we could sustain a steady-state economy for a very long time.

Figure 5.2 depicts both the accumulation of extracted minerals into

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[9] P. Sampat, From Rio to Johannesburg: Mining Less in a Sustainable World. World Summit Policy Brief #9. Online: http://www.worldwatch.org/worldsummit/briefs/20020806.html. (World Watch).

[10] N. Georgescu-Roegen, *The Entropy Law and the Economic Process*, Cambridge, MA: Harvard University Press, 1971.

[11] R. U. Ayres, The Second Law, the Fourth Law, Recycling and Limits to Growth, *Ecological Economics* 29:473–484 (1999).

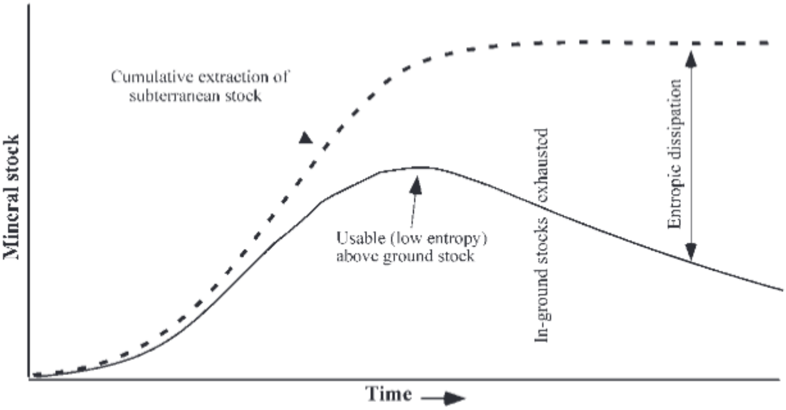

Figure 5.2 • The cumulative extraction of subterranean stock and aboveground stock of minerals over time. The distance between the two curves is a measure of entropic dissipation.

aboveground low-entropy stocks embodied in artifacts in use by (or available to) the economy (solid line) and the cumulative depletion (extraction) of subterranean stocks (dashed line) over time. We assume that initial rates of mineral extraction are low, but increase with economic growth and greater knowledge of reserve location. Eventually, however, stocks become scarcer, the costs of extraction become greater than the benefits, and extraction ceases. The point where this occurs is labeled "In-ground stocks exhausted" on the graph, and cumulative depletion ceases. In the absence of entropy, and if 100% recycling were possible and practiced, the two lines on the graph would be identical. In the real world, some portion of aboveground stocks dissipates into waste every year. The rate of increase in the aboveground stocks is equal to net annual mineral extraction minus entropic dissipation; that is, aboveground stocks are equal to minerals currently in use plus those that can be recycled.

There are two important categories of waste. Much waste is in the form of products that have stopped working, become obsolete, or simply gone out of fashion, and are discarded while still in a relatively ordered state. They are not recycled, because it is either cheaper or more convenient to extract virgin mineral flows from the Earth. For our purposes, this waste returns to the subterranean stock, though with higher entropy than the ore from which it was initially extracted.[12] Eventually, as we deplete the

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[12] Some of this material will be in a highly ordered state and have lower entropy than the same amount of mineral in the form of an ore. Georgescu-Roegen distinguishes "garbo-junk" (a bald tire useless as a tire but recyclable) from "pure waste" (the dissipated rubber particles that are not recyclable). For practical purposes, however, large stocks of ore presumably still have an overall lower entropy; otherwise waste material would be processed before the ore.

most concentrated ores, it becomes cheaper to start mining the lowest-entropy waste. For example, slag heaps near old silver mines have been mined again with newer methods. But the slag heaps resulting from the second mining will be harder to mine.

Another type of waste results from entropy in the form of mechanical or chemical erosion of the material in question. Pennies eventually wear out through use—an atom rubbed off here, another there. Other metals rust away. Hence, gross subterranean stocks are never depleted (First Law of Thermodynamics). They simply become stocks of lower and lower entropy, akin to bound energy, and are no longer of use to humans (Second Law of Thermodynamics).

We have some control over the creation of waste in the form of discarded goods, but virtually none over the effects of entropy. The entropic limit to extraction in this case occurs when the extraction process consumes more material than it can provide. As we stated earlier, some people assert that this never happens, others assert it will happen soon enough to make a steady-state economy a pipe dream, and we take the middle road.

As more minerals are brought to the surface and put to use, entropy acts on a larger stock. As more subterranean stocks are extracted, the remainder becomes more difficult to find and extract. Therefore, even before in-ground stocks are exhausted, the rate of dissipation of aboveground stocks must become greater than the net extraction of new material, and aboveground stocks begin to decline. However, even after reaching the entropic limit to extraction, we are still likely to have a large stock of material in the economy that can be reused and recycled. Over time, of course, it must gradually erode away, atom by atom. In Figure 5.2, the distance between the lines depicting cumulative extraction and aboveground stocks measures cumulative dissipation, and eventually the entire aboveground stock must succumb to entropy. This process is probably slow enough that we could achieve a steady state through material recycling for a time sufficient that extinction through evolution would happen before extinction through resource depletion. However, as is the case with oil, the threat to us is probably more from the impacts of the waste itself than from the exhaustion of mineral resources. We'll put this discussion off until we get to the section on waste absorption capacity in Chapter 6.

A resource is nonrival between generations if the use by one generation does not leave less of the resource for future generations.

What points can we draw from our discussion? First, mineral resources are rival goods at a given point in time. If I am using a hunk of steel in my car, it is not available for you to use. But through recycling, most of these resources could be made available for someone else to use in the future. Thus, we can think of *mineral resources as rival goods within a generation, but as partially nonrival between generations*, depending on how much is wasted and how much recycled. Fossil fuels are rival both within and between generations. Second, stocks of low-entropy mineral ores are finite but can be extracted at virtually any rate we choose. In contrast to fossil fuels, we have control not only over the spigot of extraction, but also over the drain by which extracted materials return to the ecosystem as waste. We open the spigot wider almost every year and do very little to close the drain, but if we shut the drain as much as possible (though it will always leak some), the open spigot matters less to future generations. Third, we could not sustain existing populations or levels of economic production in the absence of these minerals. While it would clearly be impossible to develop substitutes for all minerals, thus far it has been reasonably easy to develop substitutes for specific minerals as they become scarce, and it may be possible to keep this up for some time to come.

WATER

Earth is a water planet. Though the stock of water is finite, fully 70% of the Earth's surface is covered in water. Freshwater, however, is far less abundant, accounting for less than 3% of the total, of which less than one-third of 1% is in the form of readily exploited lakes (0.009%), rivers (0.0001%), and accessible groundwater (0.31%). Another 0.01% is found in the atmosphere, 0.31% is deep groundwater, and over 2% is in the polar ice caps and glaciers.[13] Humans are composed mostly of water, and in addition to drinking, we depend on it for agriculture, industry, hydroelectricity, transportation, recreation, waste disposal, and for sustaining the planet's ecosystem services. Water for different uses has different relevant characteristics that make generalizations difficult.

Water for drinking, irrigation, industry, and waste disposal is clearly a stock-flow resource, but a unique one. In contrast to fossil fuels and mineral deposits, many water resources are renewable as a result of the hydrologic cycle. However, for all practical purposes, many aquifers are "fossil" water, with negligible recharge rates. Many other aquifers are being mined; that is, the rate of water extraction is greater than the rate of replenishment. Even many rivers around the world, including the Colorado and the Rio Grande in North America, the Amu-Dar'ja and Syr-Dar'ja rivers that once fed the Aral Sea in Central Asia, and at times the Yellow, Hai, and Huai rivers in northern China are so heavily utilized (primarily for irrigation) that they never reach the sea.

At first glance, flowing water might appear to be a fund-service resource. In any stream or river at any given time, water is flowing at a specific rate, and the proper unit of measurement is volume/time (volume per

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[13] P. Gleick, *The World's Water: The Biennial Report on Freshwater Resources*, Washington, DC: Island Press, 2002.

unit of time), as is the case for fund-service resources. Dams, however, allow us to stockpile flowing water for later use, which is a characteristic of stock-flow resources, and water is "used up" by drinking, irrigation, industry, and waste disposal but never "wears out."

Perhaps the best way to look at flowing water is to distinguish it from the hydrologic cycle. The water itself is a stock-flow resource that is rapidly renewed by the service (provided by solar energy) of the hydrologic cycle. Hydroelectricity is not produced by water, but rather by the energy transferred to water by the hydrologic cycle—it is solar energy stored in water. Solar energy is generally a fund service, but when stored in water, it can be either a stock-flow or a fund-service resource. When mechanical energy in the water is converted to electric energy by a microhydro power plant that depends on river flow, it is essentially a fund-service resource. However, damming of the river allows the energy to be stockpiled by converting mechanical energy to potential energy, which is a stock-flow resource.

When used for transportation, recreation, or sustaining all other ecosystems on the planet, water functions as a fund-service resource. Atmospheric moisture, as part of the hydrologic cycle, is essentially a fund-service resource.

Like biotic resources, water can be a stock-flow and fund-service resource simultaneously. Unlike biotic resources, however, humans cannot meaningfully affect the total stock of water on the planet. We can and do reduce the stock of usable water, and while it is possible to restore the usability of water, there are no substitutes available for its most important uses.

As one would expect from its dual nature as a stock-flow, fund-service resource, water can be rival or nonrival depending on its use; stock-flow uses are rival, and fund-service uses are nonrival. However, as flowing water is recycled through the hydrologic cycle, it is intergenerationally nonrival. Excludability varies dramatically depending on existing institutions, though rainfall for all practical purposes is nonexcludable by nature.[14]

■ RICARDIAN LAND

Ricardian land—land as a physical substrate and location, distinct from its other productive qualities—is also a fund that provides the service of a substrate capable of supporting humans and our infrastructure, and of capturing solar energy and rain (Ricardian land does not include soil or the nutrients in the soil). A hectare of land may be capable of producing

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[14] The seeding of clouds with silver nitrate can produce rainfall in a specific location, but for practical purposes, this is basically irrelevant.

1000 tons of wheat over 100 years, but one cannot produce that wheat from the same land in an appreciably shorter period, nor would it be possible to accumulate land's capacity as a substrate.

The services provided by land are certainly excludable, and at any given point in time, they are also rival. For example, if used for farming, land provides the service of a substrate for crops. If one farmer uses that service, no one else can in the same time period. Economists often use the term "depletable" as a synonym for "rival," but the case of land suggests that this is inappropriate.[15] Using Ricardian land does not deplete it. While rival within a generation, it is intergenerationally nonrival and absolutely nondepletable.

> **THINK ABOUT IT!**
> *Why do you think we distinguish between Ricardian land as a physical substrate and the more conventional definition of land that includes the soil and its mineral content? Who or what creates value in Ricardian land? What makes land in one place more valuable than a similar piece of land elsewhere? Who or what creates value in fertile topsoil?*

SOLAR ENERGY

The last abiotic producer of goods and services we will discuss is the sun. It shines to the Earth in 19 trillion tons of oil equivalent (toe) per year—more energy than can be found in all recoverable fossil fuel stocks—and will continue to do so for billions of years.[16] Why then the fuss over the consumption of the Earth's fossil fuels?

While the flow of solar energy is vast, it reaches the Earth at a fixed rate in the form of a fine mist, and hence is very difficult to capture and concentrate. Most of the sunlight that strikes the Earth is reflected back into space.[17] Over the eons, life has evolved to capture enough of this energy to maintain itself and the complex ecosystems that life creates. It would appear that the "order" of the global ecosystem over billions of years has reached a more or less stable thermodynamic disequilibrium. A better term is "meta-stable," meaning that the global ecosystem fluctuates

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[15] When "depletable" is used in this sense, it means that one person's *use* depletes the resource in question. Hence, the ozone layer is *nondepletable* because if I use it to protect me from skin cancer, it is still there for someone else to use. It is certainly possible to deplete the ozone layer with chemicals, but that is not a case of depletion caused by use.

[16] Unless otherwise cited, estimates of energy availability are from World Energy Council, *19th Edition Survey of Energy Resources*, London: World Energy Council, 2001. Online: http://www.worldenergy.org/wec-geis/publications/reports/ser/overview.asp.

[17] N. Georgescu-Roegen, *Energy and Economic Myths: Institutional and Analytic Economic Essays*, New York: Pergamon Press, 1976.

around a steady state rather than settling into one without further variation.[18] Virtually all energy captured from the sun is captured by chlorophyll. In the absence of the evolution of some alternative physiological process for capturing sunlight, it would seem that our planet cannot sustain more low entropy than it currently does for any extended period. Yet through the use of fossil fuels, Americans are able to consume 40% more energy than is captured by photosynthesis by all the plants in the country. We also directly use over half of the energy captured by plants.[19]

As fossil fuels run out, we will need an alternative source of low entropy to maintain our economy at its current level of thermodynamic disequilibrium. The sun unquestionably radiates the Earth with sufficient energy to meet our needs, but how do we capture it? Global gross energy consumption is about 9 billion toe per year. Biomass, hydroelectricity, wind, photovoltaics, and wave/ocean thermal energy are all forms of solar energy we could potentially capture. Biomass is widely touted as a substitute for fossil fuels, but as we saw previously, converting *all* of the net primary productivity (NPP) of the United States to liquid fuel would still not meet our liquid fuel needs. Hydroelectricity currently provides 19% of global electricity, but even fully developed it could not supply 60%. Wind currently supplies little energy (about 17,500 MW in 2000), but it is a promising alternative: At current installation rates, capacity is *doubling* every 3 years.

Photovoltaics and wave/ocean thermal technologies still play very minor roles. With all of these technologies, however, large energy investments are required to produce the infrastructure needed to capture solar energy, and in many cases (e.g., photovoltaics), the energy returns on investment may be negligible. At the same time, human activity decreases the surface area of the planet covered in plant life and disrupts the ability of plants to capture sunlight. The net effect is likely to be an annual decrease in the amount of solar energy the Earth captures, and thereby a decrease in the complexity of the systems it is capable of maintaining. Figure 5.1 earlier illustrates the loss of solar energy capture that can be attributed to waste from fossil fuels.

While solar energy will bathe the Earth in more energy than humans will ever use, for practical purposes it is a fund-service resource that arrives on the Earth's surface at a fixed rate and cannot be effectively stored for later use.[20] As humans have negligible ability to directly allocate solar

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[18] E. Laszlo, *Vision 2020*, New York: Gordon and Breach, 1994.

[19] D. Pimentel and M. Pimentel, *Land, Energy and Water: The Constraints Governing Ideal U.S. Population Size*, Negative Population Growth, Forum Series, 1995. Online: http://www.npg.org/forum_series/land_energy&water.htm.

[20] Solar energy can be stored in fossil fuels, in batteries, or in the form of hydrogen for later use by humans, but this energy cannot subsequently be used to power photosynthesis, the most important function of solar energy.

energy, the fact that it is essentially nonrival and nonexcludable is not particularly important.

SUMMARY POINTS

Table 5.1 summarizes some of the policy-relevant characteristics of these five abiotic resources. Why are these details important to ecological economic analysis, and what message should you take home from this chapter? The stock-flow/fund-service distinction is important with respect to scale. We have control over the rate at which we use fossil fuels, mineral resources, and water. As the economy undergoes physical growth, it must use ever-greater flows from finite stocks. Because fossil aquifers and fuels are irreversibly depleted by use, and mineral resources may be irreversibly dissipated through use, the finite stock of these resources imposes limits on total economic production over time. Limits to growth are not apparent until the stock is nearly gone, and once gone, it is gone forever. Funds, in contrast, provide services at a fixed rate over which we have no control (though one thing that distinguishes biotic fund services from abiotic ones is that we can damage or even destroy them). Fund-services therefore limit the size of the economy at any given time, but they do not limit total production over time.

Table 5.1

SELECTED POLICY-RELEVENT CHARACTERISTICS OF ABIOTIC RESOURCES

Abiotic Resource	Stock-Flow or Fund-Service	Can Be Made Excludable	Rival	Rival Between Generations	Substitutability
Fossil Fuels (nonrecyclable)	Stock-flow	Yes	Yes	Yes	High at margin, time is important factor, but possibly substitutable
Minerals (partially recyclable)	Stock-flow	Yes	Yes	Partially	High at margin, ultimately nonsubstitutable
Water (solar recycling)	Context-dependent	Context-dependent	Context-dependent	Stocks, yes; funds and recycled, no	Nonsubstitutable for most important uses
Ricardian Land (indestructible)	Fund-service	Yes	Yes	No	Nonsubstitutable
Solar Energy (indestructible)	Fund-service	No	No, for practical purposes	No	Nonsubstitutable

Water sources are a complex mix of stock-flow and fund-service. But even the stock-flow uses of water are completely recyclable—in particular, running water is so closely linked to the fund-service of the solar-powered hydrologic cycle that it acts much like a fund-service, imposing limits on the output of the economy only at a given point in time.

Substitutability is also relevant to scale. If we can develop a substitute for a resource, then the constraints it imposes on scale are less rigid. However, developing substitutes generally relies on technology, and technology takes time to develop. In addition, truly innovative technologies are impossible to accurately predict—we could only predict one if we already knew what it would look like in which case it would not be truly innovative.

Rivalness is relevant primarily to distribution, both within and between generations. All abiotic resources are rival except for water in some of its forms and uses, and solar energy (for practical purposes). One person's use of these rival resources means they are not available for others to use, and we must be concerned about distribution within a generation. People can use the nonrival resources of solar energy and water in its fund-service functions without leaving less for anyone else, and all else being equal, we should, therefore, let anyone use them. When a good is nonrival between generations, we needn't worry about excessive use within a generation. When addressing distribution, we must remember that all natural resources are produced by nature, not humans.

Excludability is primarily relevant to allocation. The market cannot allocate nonexcludable goods, and other allocative mechanisms are required. However, in the case of sunlight and rainfall, allocation by human institutions is simply not feasible.

BIG IDEAS to remember

- Big ideas from Chapter 4 that recur in Chapter 5
- Ricardian land
- Energy return on investment
- Recoverable reserves
- P10 and P90 reserve estimates
- Net recoverable energy from fossil fuels
- Aboveground and subterranean mineral stocks
- Entropic dissipation
- Rival within versus between generations
- Garbo-junk versus pure waste
- Unique characteristics of water and solar energy