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Just south of the equator in Tanzania looms the tallest mountain in Africa, Mount Kilimanjaro, a massive stratovolcano formed by hundreds of thousands of years’ worth of ash and lava flows piled one atop the other during volcanic eruptions. The peak stands among a chain of volcanoes along a great rift in Earth’s crust, the East African Rift valley, where the African tectonic plate is splitting apart. Mount Kilimanjaro rises so high (19,039 ft, or 5803 m) that its lower slopes are shrouded in tropical rain forest while its upper peaks are dry and bitter cold, masked with white glaciers and snow. The volcano is familiar to many as a literary icon from Ernest Hemingway’s story “The Snows of Kilimanjaro,” in which he wrote: “… and there, ahead ... as wide as all the world, great, high, and unbelievably white in the sun, was the square top of Kilimanjaro.”

Today, Mount Kilimanjaro’s “unbelievably white” glaciers are nearly gone. Ascertaining the cause of their demise is a central concern of an international dialogue about the roles of scientific evidence and investigation in determining how human activities such as fossil fuel use and land cover change contribute to global warming, glacier and sea ice melting, permafrost thawing, and sea level rise, as well as a host of other, related effects. The causes and effects of global change are complex and marked by numerous feedback processes, such as when the dark rocks and sediments exposed by shrinking glaciers lead to the greater absorption of incoming solar radiation that triggers atmospheric warming and still more melting. Despite the complexity of global change, understanding its processes, causes, and effects is crucial to our well-being as a species.

In this book, we explore the Earth system’s myriad processes and feedbacks and consider the discoveries of scientists, as well as their ways of thinking, so that we can better evaluate the most pressing environmental concerns faced by humanity. To understand Earth’s interrelated processes and their impacts on humans, and to engage in ecological and physical restoration,
we need to examine the smaller systems that interact within the whole planetary system. In this chapter we:

✔ Discuss the integrative field of Earth system science.
✔ Examine the concept of systems and their components.
✔ Identify the forces that drive Earth’s processes and examine how feedback mechanisms either amplify or regulate them.
✔ Consider the field of environmental geology and the scope of this book.

### EARTH SYSTEM SCIENCE

Large ice masses at Mount Kilimanjaro and elsewhere existed during the last full glacial advance on Earth, which spanned the period from about 50,000 to 16,000 years ago. Modern glaciers worldwide are relics from that time, shrunken in size in response to the relatively stable warm climatic conditions of the past approximately 11,000 years. Since the early 20th century, however, Mount Kilimanjaro’s glaciers have withered rapidly, shrinking laterally and thinning (Figure 1-1). Reconstructions from historic aerial photos and satellite images reveal that 85 percent of the ice cover that existed in 1912 was gone by 2011. Most of the remaining glacial ice forms stagnant, isolated remnants.

In 2000, scientists drilled six ice cores in these remnants, and from the cores they were able to document nearly 12,000 years of glacial history at the summit. They discovered that glacial ice had persisted in the equatorial sun without periods of prolonged melting even through centuries-long droughts. The scientists noted that the cause of recent glacial shrinking was therefore likely to be global warming due to human activity. They added that mid- to low-latitude glaciers at high altitudes are shrinking rapidly worldwide, from the Andes and Cascades in the western hemisphere to the Swiss Alps in Europe and the Himalayas in the eastern hemisphere, so the cause of their recent demise is likely to be global rather than local or regional. The scientists also suggested that the “snows of Kilimanjaro” might be gone as early as 2015.

Garnering international attention, this tentative prediction was cited in 2006 in a well-known documentary, *An Inconvenient Truth*, which called for international action to stave off global warming. By 2010, however, it looked as if the glaciers on Mount Kilimanjaro—though further shrunk—might last a few more decades. Furthermore, another group of scientists reported that deforestation and forest fires at lower elevations in the region might have affected regional weather patterns and diminished moisture at

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**Figure 1-1** (a) Glaciers at the summit and side slopes of Mount Kilimanjaro are retreating rapidly, with about 85% of ice volume lost between 1912 and 2012. (b) Scientific investigations use data from meteorological stations and snowpits, as well as other types of evidence, in order to reconstruct the history of glaciation and determine the causes of current glacial shrinkage. (a: Cullen, N. J., Sirguey, P., Mölg, T., Kaser, G., Winkler, M., and Fitzsimons, S. J. 2013. “A Century of Ice Retreat on Kilimanjaro: The Mapping Reloaded.” The Cryosphere 7: 419–431, © 2013 the authors; b: courtesy of Douglas Hardy, University of Massachusetts)
the volcano’s summit. Based on these findings, skeptics of global warming were quick to claim that the first set of scientific studies could not verify that global warming was the primary cause of glacial shrinking. If global warming were not the cause of shrinking glaciers, the skeptics argued, it might be imprudent to make potentially costly changes in long-established habits, such as the consumption of immense amounts of fossil fuels.

As discussed in more detail in Chapter 2, science is a process, a “work in progress,” in which scientists publish the results of their investigations based on the tools available and their best understanding of the data at the time. As of 2012, for example, scientists working at Mount Kilimanjaro were able to show, through a combination of climate modeling and analysis of satellite data, that regional deforestation and drying had an insignificant effect on the demise of the snows of Kilimanjaro in comparison to the effects of human-caused global warming.

Why might melting glaciers matter? For Tanzania, the loss of famed glaciers might not affect tourism, as hikers will still want to reach the highest peak in Africa. Nevertheless, a cherished icon will be missed. For other locales where glaciers are shrinking, as in Pakistan and India, summer meltwater from glaciers is a critical resource for farming and domestic use. The reservoirs of water stored and released by glaciers serve much the same function as a dam that holds water in a valley, and if glaciers are gone that resource will have vanished, threatening the livelihoods of billions of people. Short of a major change in climate toward cooler conditions, that loss of water resources will be permanent with respect to the timescale of human interest.

The complexity of Earth system processes such as the shrinking of glaciers at Mount Kilimanjaro is typical of the environmental problems we face today and motivates our use of a holistic approach known as Earth system science. In this approach, multiple fields are integrated in the study of Earth as a system. Within the whole Earth system are many smaller, interacting components that function as systems themselves but together are dynamic parts that shape the greater entity.

Earth can be viewed as consisting of five major systems that continuously interact with one another and with solar energy, gravitational energy, and the internal heat energy of the planet to produce the climates and environments we experience at Earth’s surface (Figure 1-2). From the bottom up, these are the **geosphere** (Earth’s rocky crust and mantle and its interior metallic core), the **pedosphere** (weathered, broken particles of rock capped with soil), the **hydrosphere** (water vapor, streams, lakes, groundwater, and ice), the **biosphere** (living organisms), and the **atmosphere** (air). These systems...
tend to permeate each other. Water, for example, resides not only in large pools such as oceans and rivers but also in the soil, in the air, and in living things. Similarly, living things reside on and in rocks, soils, bodies of water, and the atmosphere. Despite these overlaps, each “sphere” is an identifiable reservoir that can be viewed as an open, dynamic system into and out of which energy and matter flow. What we mean by an open, dynamic system is discussed further below.

An Earth system science approach provides not only a physical basis for understanding our world, but also the knowledge needed to attain sustainability, a long-term condition in which development meets the needs of the present without compromising the environment or the ability of future generations to meet their needs.

Because environmental changes and geologic hazards result from the interactions of many Earth systems with one another, they need to be addressed by broadly trained Earth scientists with the ability to cross traditional disciplinary boundaries. Relevant disciplines include geology, ecology, chemistry, hydrology, soil science, atmospheric science, and climatology. As scientists learn more about the interaction of Earth systems, they can make increasingly effective recommendations for conserving resources, minimizing environmental degradation, and reducing the potential for fatalities and destruction associated with geologic hazards. They also can make better predictions, as with the timing of the demise of glaciers atop mountains in response to climate change driven by human action.

- Glaciers on Mount Kilimanjaro, the tallest mountain in Africa, have been shrinking rapidly since the early 20th century and are nearly gone; scientists estimate they will disappear within decades as a result of human-produced global warming.
- Earth system science integrates multiple fields in the study of Earth as a system within which there are smaller, interacting components that function as systems themselves.
- Primary Earth systems include the geosphere, pedosphere, biosphere, hydrosphere, and atmosphere.

### THE CONCEPT OF SYSTEMS

A **system** is a group of interrelated and interacting objects and phenomena consisting of reservoirs and fluxes. A **reservoir** is a container that holds an amount of a particular material. A kitchen sink, for example, holds a given volume of water that is maintained by pouring into the sink as much water as drains out (Figure 1-3). The content of a reservoir, whether matter or energy, is known as its **stock**. **Fluxes** are the movements of material and energy from one reservoir to another. Also called **flow rates**, fluxes are measured in amounts per unit of time. The kitchen sink is a reservoir, the amount of water that it holds at any given time is its stock, and the rates at which water flows into and out of it are fluxes.

In nature, a lake operates in a manner similar to the sink. The quantity, or stock, of water held by the lake depends on the flux of water into it from streams, groundwater, and rainfall and the flux of water out of it via streams, groundwater, and evaporation. One focus of the systems approach is to learn how systems stay in balance or change over time. We do this by measuring the fluxes of energy and matter into and out of a system and from one reservoir to another.

### Types of Systems

A system can be described as open, closed, or isolated, depending on how freely matter and energy can flow across its boundaries (Figure 1-4). An **open system** allows both matter and energy to flow in and out and is the most common type in nature. A lake is an open system because both matter (water molecules, sediment, organic materials, gases) and radiant energy from the Sun can enter and leave it. **Closed systems** are characterized by the ability to exchange energy but not matter across their boundaries, whereas **isolated systems** have no interactions with their surroundings and allow neither energy nor matter to cross. Although closed systems rarely occur naturally on Earth, for all practical
is the ability to do work, which is defined as a change brought about when a force is applied. Energy is so important to the operation of environmental systems that it is sometimes treated as a system in itself. The manner in which changes to a system occur is known as a \textit{process}; common processes that enact change in environmental systems are the formation and subduction of tectonic plates, volcanism, mountain building, erosion, and flooding. We will define and explore these processes in later chapters.

Most Earth systems are dynamic. Life on Earth, for example, is a dynamic system in which processes such as growth and reproduction are powered primarily by energy from the Sun. The state of this system has changed with time in that the numbers and types of species on Earth have increased for several billion years and occasionally have plummeted during periods of major extinctions. In contrast, the Moon is a relatively static system in which little change occurs with time, and its appearance does not alter significantly with time.

\section*{System Behavior}

In many dynamic systems, the flow of matter or energy or both into a reservoir is equal to the flow out. As a result, the stock of the material or energy remains constant with time even as the precise atoms making up that stock have changed, a condition known as \textit{steady state}. The ocean, for example, is considered to be at approximate steady state because the total amount of water and dissolved substances it contains has changed relatively little over the past few thousand years. If we look further in the past, however, we find that the dynamic ocean system was not always at approximate steady state. About 20,000 years ago, sea level was nearly 120 meters (m) lower than it is today because much of the world’s water was frozen into extensive ice sheets during the full-glacial conditions prevalent at that time. Between 16,000 and about 6000 years ago, Earth warmed, melting all but the Greenland and Antarctic ice sheets and small remnants of once larger mountain glaciers. The ocean reservoir could not maintain its former steady state because its fluxes were no longer in balance; the inflow of water from melting ice was greater than the outflow of water through evaporation. As a result, the stock of ocean water increased with time, resulting in a rise in sea level that slowed pace about 6000 years ago. It turns out that cyclical changes in Earth’s orbit around the Sun have repeatedly led to oscillations of melting and growth of ice sheets, and as a consequence, oscillatory rising and falling of sea level over tens to hundreds of thousands of years.

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Sometimes the flow of material into a reservoir exceeds the flow out for an indefinite period of time. Such behavior can lead to different rates of growth, two common types of which are \textit{linear} and \textit{exponential growth}
exponential growth curve. Human population growth is seen in Figure 1-5, however, the actual rate of increase on the number of people alive to reproduce. As can be exponential growth, in that the rate of growth depends on the number of people that is added also grows over time. The actual rate of human population growth over the past 2000 years, however, has been less gradual than the rate that would have resulted if human population growth had been truly exponential since 1 CE.

(Figure 1-5). In linear growth, inflows and outflows have fixed values and the entity growing increases in proportion to time elapsed, resulting in a linear increase in the stock of the reservoir over time. In exponential growth, on the other hand, the increase with time depends on the size of the population, such that as the stock (i.e., number of people) grows, the number of people that is added also grows over time. The actual rate of human population growth over the past 2000 years, however, has been less gradual than the rate that would have resulted if human population growth had been truly exponential since 1 CE.

The world’s human population provides an example of nonlinear growth with time. The number of people alive could be viewed as a stock, with births and deaths as the fluxes into and out of this reservoir of humankind. Some aspects of human population growth are similar to exponential growth, in that the rate of growth depends on the number of people alive to reproduce. As can be seen in Figure 1-5, however, the actual rate of increase in world population differs somewhat from that of an exponential growth curve. Human population growth is discussed in more detail in Chapter 7.

Feedbacks in Earth Systems

As systems evolve over time, processes may arise that promote further change in the direction the system is moving, a phenomenon known as a reinforcing feedback. One example of such a process is the ice-albedo (albedo refers to how much incoming solar energy a surface reflects) feedback, which occurs as a result of the interaction between Earth’s ice sheets and the atmosphere, as shown in Figure 1-6a. A small cooling of the atmosphere can lead to the growth of ice. Unlike dark surfaces, which absorb solar energy and convert it into thermal energy, the bright white surface of clean glacial ice reflects 40 to 90 percent of the sunlight that strikes it. As a result, the atmosphere above the ice cools further, which promotes the formation of more ice, which reflects more light and leads to yet more cooling. The process of glacial ice formation thus promotes still more glacial ice formation. Reinforcing feedback processes are destabilizing in that they promote a cascade of events that propel the system toward accelerating change.

A balancing feedback is a process by which a change in one direction leads to events that reverse the direction of change. Balancing feedbacks are stabilizing because they counteract the effect of the initial event and help to regulate the system so that it maintains a steady state. For example, carbon dioxide is a greenhouse gas, meaning that it absorbs energy given off by Earth’s surface and traps that energy in the atmosphere, which warms our planet. Increased emissions of carbon dioxide from burning coal in power plants and gasoline in automobiles would logically lead to global warming. The picture is much more complex, however, because a warmer atmosphere holds more water vapor, which can result in more cloud cover. Clouds can reflect solar energy back into space before it reaches Earth’s surface and is transformed into heat. The result is cooling, as shown in Figure 1-6b. Because an initial event that causes warming results in a process that leads to cooling, this chain of events is a balancing feedback process.

Clouds also can act as reinforcing feedbacks because they can absorb the energy given off by Earth’s surface. Whether the feedback effect on climate is net reinforcing or balancing depends upon the clouds’ attributes (e.g., droplet size and composition, whether ice or liquid) and their elevation above Earth’s surface. At present, global climate models do a relatively poor job of simulating cloud formation, so we cannot be certain that global warming will be offset by increased cloudiness.

- A system is a group of interconnected and interacting objects and phenomena that can be separated into reservoirs of matter and energy, connected by fluxes of matter and energy from one reservoir to another.
- In an open system, both matter and energy can flow back and forth across the system’s boundaries. In a closed system, only energy can flow across the boundaries. Isolated systems exchange neither matter nor energy with their surroundings.
- Dynamic systems are systems in motion. They display a variety of behaviors depending on the relative sizes of their inflows and outflows, whether those flows
Most Earth systems are both open and dynamic. Reinforcing and balancing feedbacks either amplify or resist changes within and among Earth systems.

Earth’s five major systems will be treated in greater detail in later chapters of this book; here, let’s consider some basic information to begin exploring Earth’s processes and the roles they play in environmental geology. Each of the major systems differs from the others in composition and physical properties (Figure 1-7). The outermost part of the geosphere, called the lithosphere (discussed below), is composed mostly of silicate minerals—solid compounds made primarily of oxygen and silicon with a few other elements including aluminum and sodium—as well as iron and nickel. The pedosphere contains elements derived from the breakdown of rock and carbon-rich organic matter and consists of solid, liquid, and gaseous compounds. The hydrosphere is mostly hydrogen and oxygen combined to form water molecules in the gaseous, liquid, and solid states. The biosphere is composed mostly of the elements hydrogen, carbon, and oxygen in the solid, liquid, and gaseous states, and the atmosphere consists chiefly of free nitrogen and oxygen in their gaseous states.

**The Geosphere: Earth’s Metallic Interior and Rocky Outer Shell**

Earth’s interior reflects the origins of the solar system 4.6 billion years ago. Based on observations of numerous galaxies, astronomers hypothesize that our Sun and its orbiting planets formed from the collapse of a massive rotating cloud of gas and dust called a nebula. Gravitational attraction drew the matter into a flattened whirling disk, with the bulk of the material at the center, where it developed into a star. Around this central star, the remaining materials in the nebula gravitated into larger bits of rock, metal, liquid, and ice that coalesced into planets.
During the first half-billion years of Earth history, so much debris was present in the solar system that Earth was bombarded constantly by meteorites—bits of rocky and metallic matter left over from the period of planet formation. As the Sun became luminous, its radiation created solar winds, which forced much of the remaining debris out of the solar system. Since then, Earth’s mass has remained essentially static, with only minor additions from cosmic dust and occasional meteorite impacts. Earth’s chemical and physical characteristics had just begun to take shape, however.

Soon after it formed from accreting debris, our planet began to heat up. Heating resulted from collision of debris, sinking of dense metallic elements into Earth’s interior, and radioactive decay of chemical elements. The temperature of the interior of Earth rose to about 2000°C, high enough to melt iron and nickel. Between 4.5 billion and 4.4 billion years ago, the intense heat of the primordial Earth melted much, or perhaps all, of its mass, initiating a process that formed concentric layers with different chemical compositions and physical characteristics.

Chemical Differentiation  Iron and nickel, the two most abundant heavy elements, sank toward Earth’s center to form the dense core of the hot, liquid Earth, located below about 2890 kilometers (km) (Figure 1-8). Lighter elements, particularly oxygen, silicon, aluminum, magnesium, calcium, potassium, and sodium, floated upward. When Earth’s surface began to cool and solidify, these elements formed a rigid crust, which is Earth’s thinnest and least dense rock layer, extending from the surface to a maximum depth of 80 km. Between the core and the crust lies the mantle, a vast layer of rock rich in oxygen, silicon, iron, and magnesium and therefore of a composition and density intermediate between the crust and light elements floated upward. (c) As a result, Earth is compositionally layered in concentric spheres from a dense core rich in iron and nickel, to a thick mantle of mostly oxygen, silicon, iron, and magnesium, and a light crust of mostly oxygen and silicon.

Figure 1-7  Composition of each Earth sphere in numbers of atoms relative to a total of 100. (Because some atoms, such as hydrogen, are very small and light, a comparison based on weight of atoms rather than number of atoms would yield different results.) Both the atmosphere and the pedosphere contain substantial amounts of nitrogen—vital to plant and animal life. In the hydrosphere, oxygen and hydrogen atoms combine to form water molecules, while the biosphere contains relatively large quantities of hydrogen, oxygen, and carbon, the elements from which living organisms are formed.

Figure 1-8  (a) Early Earth was a homogenous, rocky mixture of mostly iron, oxygen, silicon, and magnesium; there were no continents, oceans, or atmosphere. (b) During the process of differentiation that resulted from catastrophic melting of most or all of Earth’s mass, dense elements sank to the center and light elements floated upward.
and the core. Most of the rocky matter in Earth’s crust and mantle consists of silicate minerals, which are solid compounds formed largely from silicon and oxygen.

**Physical Differentiation** In addition to the chemical distinctions between Earth’s layers, there are also physical distinctions that are the result of differences in the structure of minerals and in the way they behave under different conditions of temperature and pressure. Heating a solid makes it less dense and more malleable. Compressing a solid makes it denser and more rigid. From Earth’s surface to its inner core, both pressure and temperature increase (Figure 1-9). Within Earth’s crust, the geothermal temperature gradient is about 25°C per km, although the rate differs at various locations. In other words, if you descend vertically 1000 m into a mineshaft, you will feel a temperature increase of about 25°C (77°F).

Close to Earth’s surface, the rocks of the crust and upper mantle are still fairly cool and behave in a brittle fashion, meaning that they can break when subjected to stresses. Below some depth, however, the temperature is high enough relative to the pressure of the overlying rock to cause the solid mantle to become somewhat ductile, or plastic, meaning that the rocks are capable of slow flowing movements. The depth at which this transition occurs varies around Earth and lies between 10 and 200 km below the surface. The overlying rigid layer of crust and upper mantle is called the **lithosphere**, and the underlying ductile layer is known as the **asthenosphere**. Since the lithosphere/asthenosphere transition occurs within the upper mantle, it is not associated with a compositional change such as that which characterizes the transition from the crust to the mantle.

The location of the base of the asthenosphere is not very well defined, but many geoscientists consider it to extend beneath the lithosphere to a depth of about 670 km. Below this level, increasing pressure results in a layer of dense, more rigid rock known as the **lower mantle or mantle mesosphere** (from the Greek word *mesos* for “in the middle”), which extends to about 2890 km. Between 2890 and 5150 km, the residual temperature from when Earth melted is so high that its **outer core** is still molten, despite the great pressure from the overlying rock. From a depth of 5150 km to Earth’s center at 6371 km, however, the pressure is so immense that the **inner core** is solid, even though it is compositionally similar to the outer core and at least as hot.

**Movements within the Geosphere** The brittle lithosphere is broken into more than a dozen separate plates that
The Rock Cycle In terms of a human life span, rock seems eternal. For example, the owner of land underlain by many connected caves recently built a house and gift shop directly above one of the largest caverns, now a popular tourist site in the Appalachian Mountains. To the owner, the rock beneath his home seems permanent and unchanging, despite nearby sinkholes and the cave’s evidence that over millennia rock disintegrates and changes form. Likewise, mountains seem fixed and eternal to many people, yet to the geologist they are evidence that young rocks have been pushed upward by plate tectonic processes.

The continual creation, destruction, and recycling of rock into different forms is known as the rock cycle, and it is driven by plate tectonics, solar energy, and gravity (Figure 1-11). The rock cycle begins when tectonic forces drive molten rock from Earth’s mantle toward the surface. The hot melt is less dense than the surrounding, cooler mantle rock and rises buoyantly through it, just as hot smoke rises through the cooler air around it. As the hot melt rises, it cools and freezes into igneous rock, so called from the Latin ignis, “fire.” Water, wind, biological activity, and other environmental stresses may weather the rock, dissolving and breaking it up into particles that eventually move downward and accumulate in layers of sediment (from the Latin sedere, “to sink down”). Under sufficient pressure, sediments harden into sedimentary rock. Environmental forces may again disintegrate the rock. Alternatively, tectonic forces may either drive sedimentary and other types of rock back into the mantle and remelt it into magma, or subject the rock to enough heat and pressure to transform it, without melting, into metamorphic rock.
open system into and out of which move liquids, solid particles, and gases associated with the hydrosphere, biosphere, and atmosphere. The oxygen, water, and acids abundant at Earth’s surface transform rock into pedospheric materials. Minerals weathered from rocks and sediments are mixed with organic matter produced by plants and animals to produce soil, the topmost part of the pedosphere. However, with depth and distance from the surface, the pedosphere gradually becomes indistinguishable from the lithosphere.

Some scientists have defined a part of Earth’s outermost crust as the critical zone. This near surface zone is the locus of complex interactions among rocks, water, the atmosphere, and living matter. The name “critical zone” derives from the fact that this zone regulates natural habitat and determines the availability of resources.
needed to sustain life. In a general sense, the terms *critical zone* and *pedosphere* refer to the same thing.

The total thickness of the pedosphere might be as much as 100 to 200 m in humid, tropical areas where rainfall and temperature are high and weathering processes extend deeply into the crust, or as little as 0 m in a cold, dry desert. The soil part of the pedosphere typically measures only 1 to 2 m thick, yet all terrestrial agricultural activities and food production depend on this layer for nutrients and support. Like the geosphere, soil is arranged in layers or “horizons,” with the horizon poorest in organic matter at the bottom and the horizon richest in organic matter at the top. The organic matter in soil contains essential elements that are vital to plant life, such as hydrogen, carbon, nitrogen, and phosphorus.

Rates of soil-forming processes are affected by climate, rock type, organic matter, topography, and time. Most soil-forming processes operate on time scales of thousands to millions of years, and natural processes of soil erosion generally match rates of soil formation. Unfortunately, more rapid processes of soil destruction, such as erosion due to deforestation or poor farming practices, operate on much shorter time scales—years to hundreds of years. If the rate of destruction of soil exceeds that of formation, the soil stock, or reservoir, will become depleted with time, leading to lower soil fertility.

**The Hydrosphere: Earth’s Distinguishing Characteristic**

Rain, river flow, and waterfalls are phenomena that we largely take for granted, but they do not occur on any other planet in our solar system. Earth is the only planet orbiting the Sun with abundant water and the unique combination of temperature and pressure at its surface that allows water to exist in all three states of matter: solid, liquid, and gas. Earth’s abundance of water gives the planet a shimmering, blue and white marbled appearance when viewed from space (Figure 1-13).

Water permeates all of Earth’s surface systems, yet its movement defines the *hydrosphere*, a zone about 10 to 20 km thick, extending from a depth of several kilometers in Earth’s crust to an upper limit of about 12 km in the atmosphere. If all water on Earth (1.4 billion km³) were evenly distributed, it would form a layer nearly 3 km thick. Most of Earth’s water—97 percent—occurs

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*Figure 1–12* Earth’s terrestrial surface is subject to weathering, a suite of disintegration and decomposition processes, because the geosphere is exposed to the atmosphere, hydrosphere, and biosphere. The result is the pedosphere, of which soil forms the topmost meter or so in the zone of most intense biologic activity. This view of a road cut in southern Washington shows many buried soils, or paleosols (light and dark subhorizontal bands), that record about a million years of pedosphere processes during changing climatic conditions. (Jim Richardson/Getty Images)

*Figure 1–13* Earth’s abundance of water, in all three states of matter, gives the planet’s surface a marbled blue and white appearance when viewed from space. This view, a photo taken from the Moon by astronaut William Anders in 1968, gave rise to the phrase “blue marble.” (NASA)
in the oceans and is salty because runoff from the continents brings with it dissolved rock matter in the form of ions (atoms or molecules with net electric charge). Of the 3 percent of water not in oceans, 2.7 percent occurs in solid form as ice. The remaining 0.3 percent occurs as freshwater on continents (rivers, lakes, and groundwater) and as vapor in the atmosphere.

The hydrosphere started to form about 4.4 billion years ago during the period of global melting, when some oxygen and other light elements, such as hydrogen and nitrogen, floated up from the molten Earth as gases. Because of the gravitational attraction of Earth’s mass, some of these gaseous elements—particularly the heavier ones—were unable to escape to space. Rather, they remained, some of them combining with one another, to form an envelope of gaseous matter around Earth. Although hydrogen is the lightest element that exists, it so readily combines with oxygen to form water (H\textsubscript{2}O) that much of it remained in this early atmosphere. As Earth continued to cool, the water vapor in the atmosphere condensed and rained down, filling the ocean basins. Little water has been added to or lost from the surface of Earth since the first rains that fell from the newly formed atmosphere. Although volcanic eruptions still contribute some water vapor and other substances to the atmosphere and hydrosphere today, outgassing is much less pronounced than before much of Earth cooled to a solid state.

Water in its three states migrates through a vast global hydrologic cycle at different rates and over a range of time scales in Earth’s near surface environments (Figure 1–14). As vapor in the atmosphere, water moves rapidly about the globe, on time scales of hours to days and months. The movement of water in its liquid state in streams and oceans occurs more slowly, over periods of days to thousands of years. In its frozen form, water in ice caps, ice sheets, and glaciers migrates over periods of thousands to tens of thousands of years.

Relative to other liquids, water can store vast amounts of heat energy. In areas that receive large amounts of solar radiation, water stores solar energy as heat and becomes warmer, whereas in areas that receive less solar radiation, water releases its stored heat energy and becomes cooler. As a result, the movement of water from one reservoir to another and the circulation of water within individual reservoirs such as the ocean affects local to global climatic conditions and helps to regulate Earth’s surface temperature.

![Figure 1–14 Earth’s hydrologic cycle consists of the processes (and fluxes) of precipitation, evaporation, transpiration, infiltration, and runoff from one reservoir to another. Primary reservoirs are the oceans, continental water (lakes, streams, wetlands, and groundwater), and the atmosphere.](image-url)
The atmosphere: Earth’s Envelope of Gases

The Greek word *atmos* means “vapor,” and provides the name for the atmosphere, an envelope of gases that surrounds Earth’s surface. Part of this envelope can be seen from space as swirling clouds, large masses of air that contain tiny droplets of water and ice crystals (see Figure 1-13). The atmosphere actually extends from just below the planet’s surface, where gases penetrate openings such as caves in the lithosphere and animal burrows in the pedosphere, to more than 10,000 km beyond Earth’s surface, where gases gradually thin and become indistinguishable from the solar atmosphere (Figure 1-15).

**Figure 1–15** Temperature in the troposphere declines with altitude (which here is measured logarithmically) because the troposphere is heated from below by Earth’s surface. Concentration of ozone (O₃) in the stratosphere allows temperatures to rise, but in the mesosphere they fall again. Molecular oxygen (O₂) in the thermosphere absorbs heat energy, so temperature rises with altitude. Clouds depict the location of water in the atmosphere.

**The Atmosphere: Earth’s Envelope of Gases**

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**Figure 1–16** (a) Data from NASA’s *Terra* satellite can be used to map land cover on Earth’s surface, showing the distribution of ecosystems and land use patterns. These maps aid scientists and policy makers involved in natural resource management. In general, green colors are forests, yellows to oranges and browns are cropland, grasslands, and shrublands, white is snow and ice, and gray is barren or sparsely vegetated land. (b) The vertical extent of life on Earth is referred to as the biosphere. The area below sea level is not drawn to scale. (a: Courtesy of Boston University and NASA GSFC)
The clouds of moisture so obvious in Figure 1-13 actually represent only a small portion of the gases in the atmosphere as a whole (and are an example of the overlap between the hydrosphere and atmosphere). Almost all the volume of gas in the atmosphere consists of nitrogen (78 percent), oxygen (21 percent), argon (0.9 percent), and carbon dioxide (0.03 percent). Other gases, including neon, helium, nitrous oxide, methane, and ozone, occur in trace amounts. The percentage of water vapor at the base of the atmosphere varies considerably, from 0.3 percent on a cold, dry day to as much as 4 percent on a hot, wet day, but the water content decreases rapidly to nearly zero just a few kilometers above Earth’s surface.

Venus and Mars are the most Earthlike planets in the solar system, yet they have atmospheres that consist almost entirely of carbon dioxide. The difference between their atmospheres and Earth’s seems to be related to the existence of life, because the biological activity of plants produces oxygen. Some of Earth’s oxygen combines high up in the atmosphere to form a protective layer of ozone. Other gases in the atmosphere store and transfer thermal (heat) energy at Earth’s surface, modulating the planet’s temperature and producing the weather systems that move water evaporated from the ocean basins over land where it can fall as rain or snow. If Earth had no atmosphere, its surface temperature would be at least 33°C cooler on average, or a chilly –18°C!

The Biosphere: Where Life Exists

The biosphere is a thin layer of life-forms that live in, on, and above Earth’s other environmental systems (Figure 1-16). An astonishing number of different species of organisms are thought to exist on Earth—some 8 to 9 million.8 The majority depend on photosynthesis, the process by which green plants convert solar energy, carbon dioxide, and water into food energy. These organisms thus are confined to a zone in which they can receive solar radiation. This zone overlaps part of the atmosphere, the land surface (the top of the lithosphere and uppermost part of the pedosphere), and the illuminated (euphotic) zone of water bodies (see Figure 1-16). The composition of the biosphere is similar to that of Earth’s other systems, but much closer to that of the hydrosphere than the lithosphere, as living cells are generally 60 to 90 percent water (see Figure 1-7). Like the atmosphere and hydrosphere, the biosphere is dominated by lighter elements. In fact, no elements with atomic numbers higher than 53 (iodine) are found in living cells except in trace amounts. By number of atoms, the biosphere consists of 99 percent hydrogen, oxygen, carbon, and nitrogen, and its high percentage of carbon distinguishes it from all the other major Earth systems.

Carbon atoms form strong bonds with one another, enabling them to develop elaborate chains of unlimited length, as well as rings and branching structures that can attach to other atoms and molecules. These complex organic (i.e., carbon-containing) macromolecules sometimes consist of thousands of atoms and form more compounds than any of the other 102 elements on Earth, which is one reason most chemistry students consider organic chemistry to be among their hardest courses! The fundamental organic molecules are carbohydrates, fats, proteins, and nucleic acids. All fossil fuels (oil, coal, and natural gas) were formed from organic molecules that originated in the biosphere but were buried by
sedi-ments to become part of the lithosphere after the death of the organisms that produced them.

In the early history of the planet, oxygen in the atmosphere was insufficient for animal life to exist. Instead, Earth’s primitive atmosphere contained large amounts of methane (CH₄), but these molecules were split apart by solar radiation, and the carbon combined with the little oxygen that existed to form carbon dioxide (CO₂). Early life-forms, including bacteria, blue-green algae, and phytoplankton, used the CO₂ for metabolism, producing oxygen as a by-product. Fossil evidence indicates that these early photosynthesizers existed by at least 3.5 billion years ago and perhaps earlier. With time, the amount of CH₄ in the atmosphere decreased, while the amounts of CO₂ and free oxygen increased. The continued evolution and spread of plants—which increased amounts of oxygen in the atmosphere—enabled oxygen-breathing animals to evolve. Some of these animals (herbivores) relied on consuming plant matter for energy, while others (carnivores) preyed on other animals to fuel their own metabolism. Increased levels of oxygen in Earth’s atmosphere also allowed for the formation of ozone in the upper atmosphere, which shields organisms from ultraviolet (UV) radiation given off by the sun. UV radiation can lead to sunburn, genetic defects, and cancer, so only when the atmosphere contained enough ozone could animals evolve on land.

Earth is the only planet in the solar system known to have life. The role of water in the evolution of life is essential, in part because of the many special properties of the water molecule, such as its high heat capacity. Life began in the oceans, and those life-forms that moved onto the continents carried their ocean environments with them, in their cells. It should come as no surprise, then, that the human body is nearly two-thirds water, and the water flowing through the bloodstream and bathing the cells carries on the task of the ocean by supplying the body with nutrients and removing waste products. To stay alive, terrestrial creatures require a supply of water and, consequently, are greatly dependent on the processes that involve water on land. In this sense, the biosphere and hydrosphere are intimately connected.

- The geosphere formed by accretion of rock and metal debris associated with the nebula that became our solar system. Subsequent melting of this material led to its chemical differentiation into the layers that became the inner and outer core, mantle, and crust.

- The lithosphere is a rigid, rocky layer of crust and upper mantle 10 to 200 km thick that overlies a more ductile layer, the asthenosphere, within the mantle. The lithosphere is broken into plates that float above the asthenosphere and move when heat from Earth’s interior induces flow in the asthenosphere. The outermost part of the lithosphere is a chemically distinct layer called the crust.

- The pedosphere, generally less than 100 to 200 m thick, is the entire layer of weathered rock debris and organic matter at the surface of exposed landmasses. The relatively organic-rich upper meter or so of the pedosphere, called soil, provides the nutrients essential to agricultural production on land.

- Earth’s gaseous atmosphere and largely liquid hydrosphere formed by outgassing of volatile elements from the early molten Earth as it differentiated into physically and chemically distinct layers. Both atmosphere and hydrosphere serve to modulate Earth’s surface temperatures, keeping them within a fairly limited range, by transporting heat absorbed from the Sun from one location to another.

- Because of biological activity, Earth’s atmosphere is rich in oxygen compared with the atmospheres of nearby planets. In turn, Earth’s atmosphere shields the biosphere from harmful UV rays from the Sun by efficiently absorbing them.

- The biosphere of Earth is unique in our solar system and formed soon after the early atmosphere and hydrosphere developed. It is an exceptionally thin layer, but it contains millions of different species that have evolved since the earliest, simple forms of life.

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EARTH’S ENERGY SYSTEM

Energy can be considered a sixth environmental system. Earth generates energy in its own interior and receives energy from the Sun. Energy from these two sources, plus small amounts generated from the gravitational attraction between the Moon, the Sun, and Earth, flows through all the other Earth systems (Figure 1-17). Since energy is the ability to do work, all processes and changes would cease if Earth received no energy. Earth’s access to energy and ability to use it make the planet a dynamic system.

States of Energy

Energy exists in several states, including kinetic, potential, and thermal. Kinetic energy (KE) is the energy of a body in motion and is defined as \( KE = 0.5 m v^2 \), where \( m \) is the mass of the body and \( v \) is its velocity. Potential energy (PE), in contrast, is the energy of a body that results from its position within a system. Potential energy is related to the gravitational attraction between bodies and is expressed as \( PE = mgh \), where \( m \) is the mass of the body, \( g \) is acceleration of the body due to the gravitational force, and \( h \) is the relative height of the object.

Boulders perched on a hillside contain potential energy as long as they are at rest. If a process—perhaps an earthquake—causes the ground to give way, the boulders will roll downhill under the influence of gravity. Before the rockfall begins, the rocks contain...
potential energy proportional to their distance from Earth’s center. As they roll and bounce down the slope, their potential energy is converted into kinetic energy and *thermal* (heat-related) energy (due to the motion of atoms). By the time the boulders settle at the bottom of the hill, all their potential energy has been converted into thermal energy as a result of frictional resistance. This example demonstrates a fundamental principle: Energy is completely conserved when work is done. While the energy has undergone a change in state (from potential to kinetic to thermal), the amount of potential energy before the work was done equals the amount of kinetic and thermal energy expended to do the work.

Energy can be transferred between bodies in the universe, as in the transfer of thermal energy. All bodies contain internal thermal energy, which arises from the random motions of their atoms. The term *heat* describes the transfer of thermal energy from one body to another. In a body receiving thermal energy, the added energy causes the atoms in the body to speed up. The temperature of a body is a measure of the average speed at which its atoms move. When heat is transferred to a body, its temperature rises because its atoms move faster.

Energy is measured in many different units, including foot-pounds, British thermal units (Btu), and electron volts, but the most common convention among Earth

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*Figure 1–17*  Energy is the driving force for all processes on Earth. Matter and energy flow cyclically through the hydrosphere (hydrologic cycle), biosphere (biochemical cycle), atmosphere, pedosphere, and lithosphere (rock cycle) at Earth’s surface.
scientists is to measure energy in either calories or joules. One calorie (cal) is defined as the amount of energy needed to raise the temperature of 1 gram of liquid water by 1°C and is equivalent to 4.184 joules (J). When contemplating how many calories our food contains, we refer to Calories (upper case C), each of which is equivalent to 1000 cal, or 4184 J. A candy bar, for example, contains about 400 Calories, or 400,000 calories. The human body (typically 50 to 80 kg) needs to maintain a temperature of 37°C (98.6°F). Because about 70 percent of the human body is water, much of its caloric energy is used to maintain the temperature of water at 37°C. The lower the temperature of ambient air, the greater the amount of calories needed.

**Sources of Energy**

Three sources of energy, two internal and one external, power all the processes on Earth. Our planet receives $1.73 \times 10^{17}$ watts (W; 1 W = 1 J/sec) of power (energy per unit of time) from the Sun, which amounts to 99.98 percent of its total energy budget. Smaller amounts of energy are created within Earth through spontaneous radioactive decay of some elements in rocks, and some residual heat from Earth’s formation still exists. Together these amount to $32 \times 10^{12}$ W of power. An even smaller amount of energy ($3 \times 10^{12}$ W) is supplied by the gravitational attraction within the Earth–Sun–Moon system and drives the movement of ocean water as tides.

**Solar Energy** In the Sun, hydrogen atoms at extremely high temperatures and pressures combine to form helium atoms in a process called fusion. This reaction releases radiant energy that is transmitted through space in all directions, and Earth intercepts some of this energy, warming the atmosphere, oceans, and land surface (Figure 1-18). The amount of sunlight that reaches Earth’s surface is called **insolation**, and the amount received varies around the world as well as throughout each day and season (Figure 1-19). It is large during midsummer at midlatitudes, for example, and relatively small at the same locales in winter. During photosynthesis, plants combine solar energy with water and carbon dioxide to produce the carbohydrates on which the whole biosphere depends for food and fuel. When we burn wood in a campfire, we release this stored chemical energy, which we then can use to warm ourselves or to cook food.

Under the proper geologic conditions, some biomass may be converted to oil, coal, or natural gas. These substances are called fossil fuels because they come from plants and animals that lived many tens to hundreds of millions of years ago. When we drive cars, we are using solar energy that is many tens to hundreds of millions of years old! The amount of energy stored within fossil fuels is extremely small compared with the amount of solar energy received by Earth, because less than 1 percent of incoming solar energy is converted to chemical potential energy by plants. In less than a single month, Earth receives as much energy from the Sun as is stored in known fossil fuel reserves. Because fossil fuels that were easiest to reach and extract have diminished, solar energy is an increasingly important energy source.

**Earth’s Internal Energy** Earth makes its own supply of internal energy through the spontaneous decay of certain elements in minerals. In this process, known as radioactive decay, parent atoms convert to other atoms by losing or gaining subatomic particles in their nuclei (discussed more fully in Chapter 6). This process releases relatively small amounts of thermal energy that are transferred through the surrounding rock.

Although much smaller than the influx of solar energy, it is Earth’s internal heat energy that drives
lithospheric plate motions, which in turn result in earthquakes and volcanism. As plates move, energy can be stored in rocks, much as energy is stored in an elastic band by stretching it. When such rocks finally snap, as would a band that had been stretched too far, the amount of energy released can be quite large. The 2004 Indonesian earthquake that led to the Indian Ocean tsunami, in which more than 275,000 people perished, released about $1.1 \times 10^{17}$ J of energy, equivalent to more than 1500 nuclear bombs the size of those dropped on Hiroshima, Japan, during World War II.

**Gravitational Attraction** Earth derives energy from gravitational attractions between itself and the Moon, the Sun, and the other bodies in the solar system. Although minor compared even with Earth’s internal energy, the energy derived from gravitation causes both Earth’s crust and ocean water to change shape over time in a regular fashion, resulting in rock tides as well as ocean tides.

**Energy Budget of Earth**

The energy system of Earth is in a steady-state condition; the amount of energy received by the whole Earth system is approximately equal to the amount of energy flowing out of the system. Because the Sun supplies all but 0.02 percent of Earth’s energy, the inflow and outflow of solar energy is a close approximation of Earth’s energy budget. An energy budget, like a monetary budget, is an accounting of inputs and outputs, and a steady-state condition is like a balanced financial budget.

As shown in Figure 1-18, more than half of all incoming solar radiation is returned to space before doing any work at Earth’s surface. About 25 percent is reflected to space by particles or clouds in the atmosphere and another 5 percent is reflected by Earth’s surface, while 25 percent is absorbed by clouds and the atmosphere. This leaves about 45 percent of incoming solar radiation to be absorbed by Earth’s surface. About two-thirds of this absorbed energy (29 percent of the original incoming radiation) is cycled through Earth’s environmental systems and reradiated, while one-third (16 percent of the original incoming radiation) is converted to heat (thermal energy). The wavelengths of reradiated energy are longer than those of the original (or reflected) solar radiation. Because clouds and greenhouse gases such as carbon dioxide trap energy at longer wavelengths relatively easily, reradiated energy has a strong influence on

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**Figure 1-19** Insolation is the amount of sunlight that reaches Earth’s surface during a given time period, as shown here for July 1, 2012 through July 31, 2012. It commonly is measured in units of watts per square meter of land surface

(W/m$^2$). Note how little sunlight is received by the south polar region during July, which is winter for the southern hemisphere. (NASA)
Earth’s climate. In Figure 1-18, you can see that inflow of solar energy is equal to outflow, with 30 percent of the inflow leaving Earth as reflected energy and 70 percent leaving as reradiated energy. Earth’s energy budget is balanced.

**Human Consumption of Energy**

Humans have devised many methods to harness energy. For millennia, people have used wood for heat and wind and moving water to grind grains and process other commodities in mills; more recently, a variety of fossil fuels and other energy sources generate electricity (Figure 1-20). In Iceland, a country located on an active plate boundary with volcanism and high heat flow at the surface, the dominant energy source is geothermal. Worldwide, however, fossil fuels (largely coal, crude oil, and natural gas) have become the most important sources of energy during the past century.

The total amount of energy used has increased with time even though the dominant energy sources have varied. In 2011, humans used a staggering 487 exajoules (an exajoule equals 10\(^{18}\) joules) of energy worldwide, much of it to generate electricity. As a consequence, our planet—particularly due to its more populated areas—resembles a well-lit black marble at night (Figure 1-21).

The amount of incoming solar energy is roughly 12,000 times that of the world’s current energy consumption, but relative to the amount available, little solar energy has been collected and used thus far. Most industrialized nations rely heavily on fossil fuels—oil, coal, and natural gas—to power cars, heat homes and water, and generate the electrical energy needed to run various appliances and utilities. However, Germany, Spain, and the United States currently are making significant advances in technologies in order to use more solar energy for heating and electricity.

Of all the different sources of energy available to the world, fossil fuels satisfy about 81 percent of total energy demand. However, the type of fuel used and the per capita use of energy vary markedly from country to country, as well as from region to region within countries. As of 2010, the United States used more total energy than any other country in the world except China. With only about 5 percent of the world’s population, the United States consumes about 19 percent of the world’s annual primary energy demand (98 quadrillion Btu in 2010). In 2010, China surpassed the United States to become the world’s leading consumer of energy, using 20.3 percent of the total. Still, its far greater population means that China’s per capita energy consumption remains lower than that of the United States.

Three sources of energy are responsible for all processes on Earth: solar energy, internal thermal energy, and gravitational energy.

**Human Population and Earth System Boundaries**

Several related issues have contributed to a growing environmental awareness since about the mid-20th century, foremost among them population growth and spreading industrialization. With population and industrial growth come ever-increasing demands for such resources as fuel, land, and clean freshwater. Environmental degradation is the nearly inevitable result
of these pressures and demands. In addition, although people always have lived in areas prone to earthquakes, floods, and other geologic hazards, the increasing numbers of people living in these areas heightens the potential for human disaster.

**Human Population Growth**

As the world’s population passed 7 billion sometime in late 2011 to early 2012, concern continued to mount over how many more people would be added in the future. Human population growth has been difficult to predict accurately because it depends on a large number of variables—from advances in agriculture, sanitation, and medicine to the influences of culture, religion, and medical practices. The rate of human population growth has varied throughout human history, but its most striking feature is marked growth into the billions in the last few hundred years (see Figure 1-5).

The human population has grown in a manner somewhat similar to exponential growth. It took 2 million years of human history to add the first billion people, 130 years to add the second billion (around 1927), 30 years to add the third (1960), 15 years to add the fourth (1975), and 12 years to add the fifth (1987). World population reached 6 billion in 1999 and 7 billion in 2011–2012, with each extra billion added after 12 years. Since the 1960s, annual growth rates for world population have declined from a high of roughly 2.2 percent to about 1.1 percent in 2012. As fertility and mortality rates change, population growth rates vary. The current slowdown in population growth rate is a result of falling levels of fertility.

Despite a decreasing rate since the 1960s, population growth still has considerable momentum because of the large number of people on Earth. Even at the relatively low growth rate of 1.1 percent, another 75 million people are added to Earth’s population each year. Most population growth is occurring in developing rather than already industrialized countries. Various predictions of the world’s future population range from 6 to 16 billion people during the next century.

What are the consequences of more than 7 billion people on Earth and a growing population with a desire for higher standards of living? To date, consequences have included increasing use of resources (e.g., minerals, fertilizers, and water), consumption of energy, and production of wastes. Unfortunately, they also have included a growing number of extinctions of plant and animal species.

More people are living in cities; in fact, more than 50 percent of people live in urban areas, and cities are increasingly larger. In the early 20th century, only 20 percent of the population lived in urban areas. As a result, population density, not just population, is increasing (Figure 1-22).

The world’s first megacities, those with more than 10 million people, developed in the mid-20th century
A resource is anything we get from our environment that meets our needs and wants. Some essential resources, including air, water, and edible biomass (plant and animal matter), are available directly from the environment. Other resources are available largely because we have developed technologies for exploiting them. These include oil, iron, and groundwater. In general, people in affluent and highly industrialized countries use far more resources than are required for basic survival. The United States, for example, has only 4.8 percent of the world’s population, yet it consumes about 33 percent of the world’s processed nonrenewable energy and mineral resources.

Resources are classified into three major types according to their degree of renewability: potentially renewable, nonrenewable, and perpetual (Figure 1-23). Potentially renewable resources can be depleted in the short term by rapid consumption and pollution, but in the long term they usually can be replaced by natural processes. The highest rate at which a potentially renewable resource can be used, without decreasing its potential for renewal, is its sustainable yield. If the sustainable yield is exceeded, the base supply of the resource can shrink so much that the resource can become exhausted—used up. Soil formation, for

Figure 1–22 World population density on average is about 50 people per km² of land area, excluding Antarctica, but can be as high as 40,000 people per km² in megacities. Note that the four most densely populated places are Singapore, Hong Kong, Bahrain, and Bangladesh. The four largest megacities are all located in Asia: Tokyo, Japan; Jakarta, Indonesia; Seoul, South Korea; and Shanghai, China. (Image by Robert Simmon, NASA’s Earth Observatory, based on data provided by the Socioeconomic Data and Applications Center [SEDAC], Columbia University)
example, occurs at rates of about 2 to 3 centimeters (cm) per thousand years, making it a potentially renewable resource. Unwise farming practices, however, can cause soil loss of 6 to 8 cm per decade. Soil cannot be renewed at this rate because its formation is dependent on plants and soil moisture, both of which are gone once the soil itself is lost. In some parts of the world, all soil has been removed and so is essentially nonrenewable.

**Nonrenewable resources**, such as fossil fuels and metals, are finite and exhaustible. Because they are produced only after millions of years under specific geologic conditions, they cannot be replenished on the scale of a human lifetime. The formation of oil, for example, requires that buried plant and animal matter be subjected to tens of millions of years of squeezing and heating by geologic processes, a rate of formation so slow that the resource cannot be considered renewable.

Some nonrenewable resources, such as copper and iron, can be recycled or reused to conserve the supplies. **Recycling** involves collecting, melting, and otherwise reprocessing manufactured goods. Resources commonly recycled include aluminum, paper, and iron. **Reuse** involves repeated use of manufactured goods in the same form. Glass bottles commonly are reused. Other resources, such as fossil fuels, cannot be recycled or reused because their combustion during energy production converts them to ash that falls to Earth, exhaust fumes that go into the atmosphere, and heat that ultimately leaves Earth as low-temperature radiation. Nonrenewable resources become economically depleted when so much—typically about 80 percent of the resource—is exploited that the remainder is too expensive to find, extract, and process. Oil buried in rocks deep beneath the Antarctic ice sheet, for example, would be far more expensive to find, extract, and refine than oil trapped beneath the shallow salt beds of Texas.

**Perpetual resources** are those that are inexhaustible on a human time scale of decades to centuries. Examples include solar energy—which has fueled numerous reactions and processes on Earth for its entire 4.6-billion-year history, heat energy from the interior of the Earth, and energy generated by Earth’s surface phenomena such as wind and water flowing downhill.

One of the most significant changes in human history is the increased demand for, and use of, energy. Before the Agricultural Revolution started about 10,000 years ago, people’s energy demands were primarily for food. On average, a person uses about 10 megajoules (MJ) of energy (2000 to 3000 food calories) per day, and for early humans this was the bulk of their energy needs. By 2011, however, daily per capita energy consumption in the United States was more than 900 MJ, spent mostly in industry, transportation, and temperature control. Much of this energy consumption goes toward the production and transport of food.

**Figure 1–23** (a) Soil, a potentially renewable resource, is put at risk by the demands for food associated with worldwide population growth. (b) New technologies and ever-larger machines are used to mine coal, a nonrenewable resource, at increasing rates. (c) Solar energy is a perpetually available resource. Reflective panels can focus this energy on a “power tower” where it is converted into electricity. (a: Hopsalka/Shutterstock; b: J. van der Wolf/Alamy; c: Felipe Rodriguez/Getty Images)
in automobile engines and industrial power plants and released into the atmosphere. These molecules react with gases and water vapor in the atmosphere to produce smog and acidic rainwater, both of which make the air and water unhealthful, causing damage to plants, fish, land animals (including people), and even stone.

Wastes are unwanted by-products and residues left from the use or production of a resource. Early human habitation sites are often identifiable by the piles of waste left behind, including shells, bones, charcoal from fires, and broken pottery. Sometimes, early humans reused wastes in innovative ways, building huts from animal bones, for example. People tended to move on when their waste piles became substantial, although substantial amounts of human detritus can be found beneath cities that date to ancient times, such as Rome and Paris. Most waste piles made by small bands of people were biodegradable, so they did little long-term environmental damage. In contrast, modern humans in industrialized societies have much higher population densities and technologies that enable them to concentrate large amounts of waste, some of which is toxic and infectious, in small areas.

A Model of Environmental Impact

Scientists have developed a simple model of environmental degradation and pollution to assess the environmental impact of human populations. In this model, the extent of the environmental impact depends on three variables: (1) population, (2) per capita consumption of resources, and (3) the amount of environmental degradation and pollution per unit of resource used:

\[
\text{Number of people} \times \text{per capita consumption} \times \text{degradation and pollution per unit of resource used} = \text{environmental impact}
\]

A Model of Environmental Impact. As demand for a resource increases, more of it is produced. For nonrenewable resources, production cannot increase forever, because ultimately the resource will be exhausted. Renewable resources can provide lasting supplies if the rate of production is similar to the rate of renewal. Only for perpetual resources is unlimited increase in production possible.

Production and consumption of renewable, nonrenewable, and perpetual resources follow different growth curves (Figure 1-24). For potentially renewable resources, such as wood, the curve is similar to that of the growth of a biological population: Production rises exponentially for some time, and then levels off at a state of no growth that is equal to the rate of replenishment. For nonrenewable resources, such as fossil fuels and minerals, production rates rise exponentially, reach a maximum value, and then decline exponentially as supplies approach zero. For perpetual resources, such as solar energy, production can rise exponentially for essentially unlimited time periods. It is clear that humans can rely on nonrenewable energy resources only for a limited time, before turning to a perpetual source of energy.

Pollution, Wastes, and Environmental Impact

Many of the world’s environmental problems are related to the wastes produced by human activities. To a greater or lesser extent, all humans produce wastes that pollute and degrade air, water, and land. Pollution is the contamination of a substance with another, undesirable material. Environmental pollution results when a pollutant degrades the quality of an environment.

Common pollutants in urban areas are sulfur dioxide (SO₂) and oxides of nitrogen (NOₓ, molecules with one or two atoms of oxygen and one atom of nitrogen), all of which are created by combustion of fossil fuels...
examples is the United States, which has less than 5 percent of the world’s population but consumes more than 33 percent of nonrenewable energy and mineral resources and produces more than a third of the world’s pollution. As a result, despite its relatively small population, it has a tremendous environmental impact. In contrast, China has about 19 percent of the world’s people, about four times as many as the United States, but causes less than one-tenth (or 10 percent) the environmental damage of the United States. For this reason, it sometimes is noted that the environmental impact of one person in the United States is equivalent to that of many more persons in developing nations, such as India, where resource use and pollution per person are much smaller.

As nations develop, the extent of their environmental impact due to consumption changes rapidly. In the 19th century, for example, during a rush to settle all parts of the United States, forests were destroyed to clear fields for farming, and many other sites were severely degraded by destructive mining practices. Since then, increasing environmental awareness in the United States has resulted in significant efforts to prevent such degradation in future development. Likewise, as China enters the global market of free trade and as other nations become more developed, it is likely that the nature of their environmental impacts will change.

The third component of environmental degradation is pollution per unit of resource used. In some cases, the amount of pollution produced per unit of resource used is so high that extreme environmental degradation occurs. For example, the increased use of coal for energy in China at a time of rapid industrial growth is resulting in substantial air pollution problems (Figure 1-25). Industrialized countries in Eastern Europe and the former Soviet Union have amassed a legacy of environmental pollution that will affect their citizens for decades to come.

Minimizing Environmental Impacts  Solving the problem of environmental degradation caused by rapid population growth is essential, but the solution is not simple. Increasing access to medicine and sanitary supplies of water worldwide has reduced death rates and thus contributed to the rapid population growth of the past few centuries. As a result, reducing population will require a change in the birth rate. Solutions for reducing birth rates are related to education and standards of living, among other things. In most countries of the world, the higher the level of education and standard of living of women, the more likely women are to use birth control methods and have fewer children.

Reduced birth rates in most developed nations, as well as in China and India, caused worldwide population growth rates to drop from 2.06 percent in the late 1960s to 1.73 percent in the late 1970s, to 1.6 percent in the 1990s, and to 1.1 percent as of 2012. This consistent drop in population growth rates is encouraging, but rates must drop in many more nations in order to level off global population growth.

Minimizing environmental degradation caused by consumption can be achieved through reduced resource consumption per person and coordinated efforts to recycle or reuse products. Minimizing environmental degradation caused by pollution can be achieved through environmental regulation and the use of more efficient technologies to minimize the amount of waste (much of which produces pollution) generated during industrial and resource extraction processes. Efforts to develop waste minimization procedures for different industries are now the focus of research and testing at many universities and industrial labs. Some new factories in Denmark, for example, produce nearly zero waste, designing their activities so that waste products from one stage are used as input to other stages of the manufacturing process.

As environmental regulations become more stringent, companies are developing new technologies to extract and process resources that produce fewer wastes than ever before. New methods to mine copper that require no excavation have been developed in Arizona and now are in use elsewhere (see Chapter 4). The copper is removed from sediments and rocks by solution techniques, so that heating and melting of rocks to separate precious metals are not required. The result is a substantial (or nearly complete) reduction in the production of fumes, noxious gases, and ash that once was typical of mining operations.

Figure 1–25 In China, environmental pollution and degradation are extreme as a result of a large population, rapid industrialization, and heavy reliance on burning coal for power. (Bernard Wis/Paris Match/Getty Images)
of the exhaust material belched from smokestacks at mine sites.

**Natural Disasters, Hazards, and Risks**

In contrast to environmental issues associated with population and pollution are geologic hazards that exist regardless of human activity but can put people in harm’s way as a result of human activity. For example, people who live near a volcano put their lives and property at risk in the event of a volcanic eruption. Although a volcanic eruption could occur regardless of whether or not people live nearby, the fact that they do live in the vicinity leads to a risk and potential for disaster.

A geologic hazard is a natural phenomenon, process, or event with the potential for negative effects on human life, property, or the environment. Examples include floods, tornados, hurricanes, volcanic eruptions, earthquakes, and landslides. Poorly consolidated sediment on a steep slope, for example, could pose a hazard to those living in a development on that slope. If slope failure, known as a landslide, occurred during a heavy rainfall event, destroying homes and killing residents, it would be a disaster.

Natural disasters typically are sudden environmental changes that happen as a result of longer-term geologic processes and have significant impacts on human life and property. The geologic hazard of earthquakes, for example, is the result of hundreds or thousands of years of accumulation of geologic deformation, but the breaking point that causes an earthquake occurs relatively suddenly.

Natural disasters can pollute the environment just as human-made disasters, such as oil spills and air pollution from factory smoke. Carbon dioxide gas seeping from a volcano in Cameroon, Africa, for example, accumulated at the bottom of a lake in a crater atop the volcano and suddenly belched from the lake in 1981. The geologic event suffocated and killed thousands of sleeping villagers within minutes.

Volcanic eruptions and earthquakes, geologic hazards caused by the interior processes that move Earth’s tectonic plates, occur with little impact from human activities; an exception is wells that inject wastewater underground, which have been documented to cause relatively small earthquakes. Floods and landslides, in contrast, are geologic hazards that can be worsened markedly by human activities. Removing natural vegetation from hillslopes, for example, can increase the runoff of rainwater and thereby increase flooding in streams. Removing vegetation also destroys roots, which anchor the soil on the slopes. Landslides occur when loosened soil and other debris slips suddenly downhill.

Risk refers to the magnitude of potential death, injury, or loss of property due to a particular hazard. The risk of death in the United States each year by an earthquake or volcano (less than 0.1 death per million people) is far less than the risk of death by automobile accidents (120 deaths per million people) or fires (11 deaths per million people). Different regions have different risks; in California, the risk of death by earthquakes and volcanoes is greater than it is in Ohio or Kansas. In fact, much of the United States west of the Rocky Mountains is considered to be a high-risk area for earthquakes, and all active volcanoes are in western states. Nevertheless, some parts of the central and eastern United States have been devastated by large earthquakes in the past, and in some ways are even more vulnerable to damage than western areas (see Chapter 3).

**The Anthropocene and Planetary Boundaries**

As the human population and individual standards of living have risen, our species has become the dominant influence on many Earth systems. From increases in greenhouse gases that warm the atmosphere to changes in biogeochemical cycles or wholesale reorganizations of landscapes and water supplies, our species is leaving its mark on the surface of planet Earth. Some Earth scientists, in fact, have suggested that changes from human activities are so substantial and widespread that a new geologic era could be added to the geologic time scale, one called the Anthropocene.10

Decisions made now will determine whether future generations inherit a degraded planet quite different from the one we live on presently, or a planet capable of providing for human and ecosystem needs over the long term. In 2009, sustainability scientist Johan Rockström and his colleagues published a paper entitled “Planetary Boundaries: Exploring the Safe Operating Space for Humanity.” In it, they identified Earth system processes critical to human well-being and assessed how those processes have been altered by human hands. They noted that the past 11,000 years, a warm period called the Holocene epoch that postdates a major glacial advance and cold period, has been a time of relative stability. During that time people developed agriculture and irrigation, built permanent settlements that became cities, and made phenomenal technological advances that recently included exploring outer space and sending a remotely controlled rover to Mars.

The scientists cautioned, however, that this long-term stability might be transitory and that human activity might be capable of tipping Earth into entirely new environmental states that could be disruptive to society. They sought to identify thresholds for critical
environmental processes that might lead to such tipping points. Operating within a safe space for humanity, within the limits of what the scientists called planetary boundaries, requires staying within those thresholds and not reaching those tipping points.

Rockström and his colleagues developed a list of nine factors for which exponential growth of the human population and its associated consumption of resources and generation of wastes could exceed these limits and threaten planetary stability (Figure 1-26). These nine boundaries range from local to global in their scale of process, and the threshold behavior of each ranges from slow, with no evidence of planetary scale behavior, to sharp and global in scale. The boundaries include the global cycling of major nutrients critical to life, climate, and other Earth systems (i.e., the biogeochemical cycles of nitrogen, phosphorus, and carbon); the global cycling of water; changes in land use; the loss of biodiversity that is critical to self-regulating the biosphere’s resilience; aerosol loading to the atmosphere; and chemical pollution.

While the absolute values of planetary thresholds are uncertain, the idea that Earth systems are interconnected and that humans are having a marked impact on these systems is clear. Along with other topics, we address the planetary boundaries identified by Rockström and his colleagues in the chapters of this book. In carrying out our analysis we make use of the deep time perspective of Earth science, which provides us with myriad examples of former planetary states quite different from the present. In the last chapter of this book, we revisit the ideas of planetary boundaries and humanity’s safe operating space.

- As Earth entered a period of relative global warmth about 10,000 years ago, people began to develop agriculture (the Agricultural Revolution) and, since then, they have altered dramatically the composition of ecosystems on Earth. The environmental ramifications of agriculture have been substantial.

- Since the Agricultural Revolution, the rate of human population growth has been rapid, accelerating in the years since the Industrial Revolution. Most of the recent growth is attributed to a decrease in death rates because of better sanitation and medical care.

- With industrialization has come a marked increase in consumption of energy, in particular the use of nonrenewable sources of energy (fossil fuels).

- Decreasing environmental degradation would require that population growth stabilize; that we

![Figure 1-26](image-url) Scientists have identified nine planetary boundaries that range in scale of process from local to global (bottom to top), and in scale of threshold for potential change from slow with no known global-scale threshold (right) to possibly sharp with a global-scale threshold (left).
develop perpetual sources of energy, such as solar energy; and that we decrease the use of nonrenewable resources that require extensive mining and that produce pollutants.

- As human population increases, so does the risk associated with natural geologic hazards such as flooding, landslides, earthquakes, and volcanism. Mitigating natural disasters requires increased effort from geoscientists—to understand natural phenomena and their causes, and from all of us—to plan wisely when selecting places to live and work.

**CLOSING THOUGHTS**

We began by discussing the possible causes of rapidly shrinking glaciers atop the highest mountain in Africa, Mount Kilimanjaro. This example shows how Earth scientists investigate interconnected Earth systems. Greenhouse gases emitted from activities that include burning fossil fuels for energy lead to global warming that, in turn, can cause glacial ice masses to shrink and change the fluxes and stocks of water in Earth’s hydrosphere. We also examined the ways in which scientists investigate Earth processes, using a multitude of tools and an overarching view of Earth as a dynamic system. By systematically examining each of the parts and processes within our planet’s various subsystems, Earth scientists are able to determine cause and effect and to predict future outcomes.

The scale of human impact on Earth is relatively small in comparison with that of geologic processes such as volcanism, continental drift, waxing and waning ice ages, or mountain building, yet humans are by no means an insignificant force. The signatures of human activities can be detected worldwide, from extinct species to wholesale changes in land cover or the composition of our atmosphere. Whether or not the ongoing anthropogenic changes in the cycling of matter and energy on Earth result in an environment in which we can live sustainably and within planetary boundary thresholds remains to be seen.

**SUMMARY**

- Earth is best understood from an Earth system perspective because the activities of our planet are interrelated by the cycling of matter and energy through Earth’s various systems.

- The environment can be divided into six major systems: the geosphere (rock), pedosphere (weathered rock and soil), hydrosphere (water), atmosphere (air), biosphere (life), and energy system.

- Cycling of matter and changes in the Earth system are the result of processes that are driven by energy—solar energy, the energy from radioactive decay of minerals in Earth, and gravitational energy.

- Geologic processes, such as plate tectonic movements or volcanism, can affect multiple Earth systems over a period of time, each change resulting in another.

- Earth systems are characterized by both reinforcing and balancing feedback processes when they respond to changes in conditions.

**KEY TERMS**

- Earth system science (p. 5)
- biosphere (p. 5)
- atmosphere (p. 5)
- sustainability (p. 6)
- reservoir (p. 6)
- stock (p. 6)
- fluxes (p. 6)
- open system (p. 6)
- closed systems (p. 6)
- isolated systems (p. 6)
- dynamic system (p. 7)
- static system (p. 7)
- energy (p. 7)
- steady state (p. 7)
- linear growth (p. 7)
exponential growth (p. 7)
reinforcing feedback (p. 8)
balancing feedback (p. 8)
silicate minerals (p. 9)
core (p. 10)
crust (p. 10)
mantle (p. 10)
lithosphere (p. 11)
asthenosphere (p. 11)
lower mantle (p. 11)
mantle mesosphere (p. 11)
outer core (p. 11)
inner core (p. 11)
rock cycle (p. 12)
igneous rock (p. 12)
sedimentary rock (p. 12)
metamorphic rock (p. 12)
silicate minerals (p. 9)
core (p. 10)
crust (p. 10)
mantle (p. 10)
lithosphere (p. 11)
asthenosphere (p. 11)
kinetic energy (KE) (p. 18)
potential energy (PE) (p. 18)
thermal energy (p. 19)
insolation (p. 20)
resource (p. 24)
potentially renewable resources (p. 24)
nonrenewable resources (p. 25)
perpetual resources (p. 25)
pollution (p. 26)
overpopulation (p. 26)
overconsumption (p. 26)
pollution per unit of resource used (p. 27)
geologic hazard (p. 28)
natural disasters (p. 28)
risk (p. 28)
planetary boundaries (p. 29)

**REVIEW QUESTIONS**

1. Explain how scientists do research aimed at determining the cause(s) of shrinking glaciers on mountains such as Mount Kilimanjaro.
2. Why are Earth’s systems considered to be open? Why is the whole Earth system considered to be closed?
3. Is the amount of annual solar radiation (energy) reaching Earth’s surface an example of a flux or a stock?
4. How and when did the geosphere, hydrosphere, pedosphere, atmosphere, and biosphere form on Earth?
5. How are the lithosphere and crust different from each other?
6. What are the major processes that operate in the lithosphere and rock cycle?
7. What are the major processes that operate in the hydrosphere?
8. What are the two most abundant elements in Earth’s modern atmosphere?
9. What are the three main sources of energy on Earth?

**THOUGHT QUESTIONS**

1. What do you predict would happen if the flux of rock from Earth’s mantle were to increase? For example, there is some evidence that periods of intensified volcanic activity have occurred during Earth’s history. How would this affect the rock cycle?
2. Development of an area that was tropical forest results in removal of all vegetation and exposure of bare soil. Rainfall runs off the devegetated surface and increases the flow of water in streams. Increased runoff also has greater power to remove soil, thus causing erosion. As the amount of soil decreases, the amount of infiltration of rainfall into the soil is lessened, resulting in even more runoff, and consequently even more soil erosion. Is the preceding an example of a reinforcing or a balancing feedback? Explain your answer.
3. Why would scientists try to model Earth systems? What would be the benefits and limitations?
4. Why can’t plants (and hence food or trees) be grown easily in the pedosphere if the upper meter or so of soil is eroded away?
5. Can the oceans ever contain more water than they do at present, and hence result in a rise in sea level? Can they ever contain less water than at present, and hence result in a drop in sea level? Has either of these types of change occurred in Earth’s history?
SUGGESTED READINGS


