3. Which does NOT contribute to atmospheric convection currents?
   (a) Hadley cells
   (b) gyres
   (c) polar cells
   (d) the intertropical convergence zone
4. The maximum amount of water vapor air can hold at a given temperature is called the
   (a) saturation point.
   (b) absolute humidity.
   (c) dew point.
   (d) vapor pressure.
5. The Coriolis effect is responsible for
   (a) the convergence of two ascending Hadley cells.
   (b) the location of atmospheric currents caused by the unequal heating of Earth.
   (c) the cooling effect of air as it rises and expands.
   (d) the deflection of atmospheric currents.
6. Which does NOT play a role in causing a rain shadow?
   (a) cold polar air
   (b) a mountain range
   (c) adiabatic cooling
   (d) humid ocean air
7. Which is the correct order of the convection cells, starting from the equator?
   (a) Ferrell, Hadley, polar
   (b) polar, Hadley, Ferrell
   (c) Hadley, Ferrell, polar
   (d) Hadley, polar, Ferrell

MODULE 11

Ocean Currents

We have seen that the unequal heating of Earth together with the Coriolis effect drives air currents around the world. These two phenomena also affect ocean currents. In this module, we will explore the circulation of ocean waters, both at the surface and in the deep ocean. We will see how ocean circulation affects the transport of heat around the globe, how this heat movement affects the climates of continents, and how disruptions to these circulation patterns can dramatically alter global climates.

Learning Goals

After reading this module you should be able to

- describe the patterns of surface ocean circulation.
- explain the mixing of surface and deep ocean waters from thermohaline circulation.
- identify the causes and consequences of the El Niño–Southern Oscillation.

Surface ocean currents move warm and cold water around the globe

The flow of ocean water is an important factor for global climates because it moves warm and cold waters to different parts of the globe. For example, the Gulf Stream is a current of warm water that emerges from the Gulf of Mexico and warms much of the eastern coast of the United States. In doing so, ocean currents affect the primary productivity found in different ocean regions as well as the climate of the adjacent continents. When warm ocean currents flow from the tropics to higher latitudes, the neighboring continents receive warm air from the

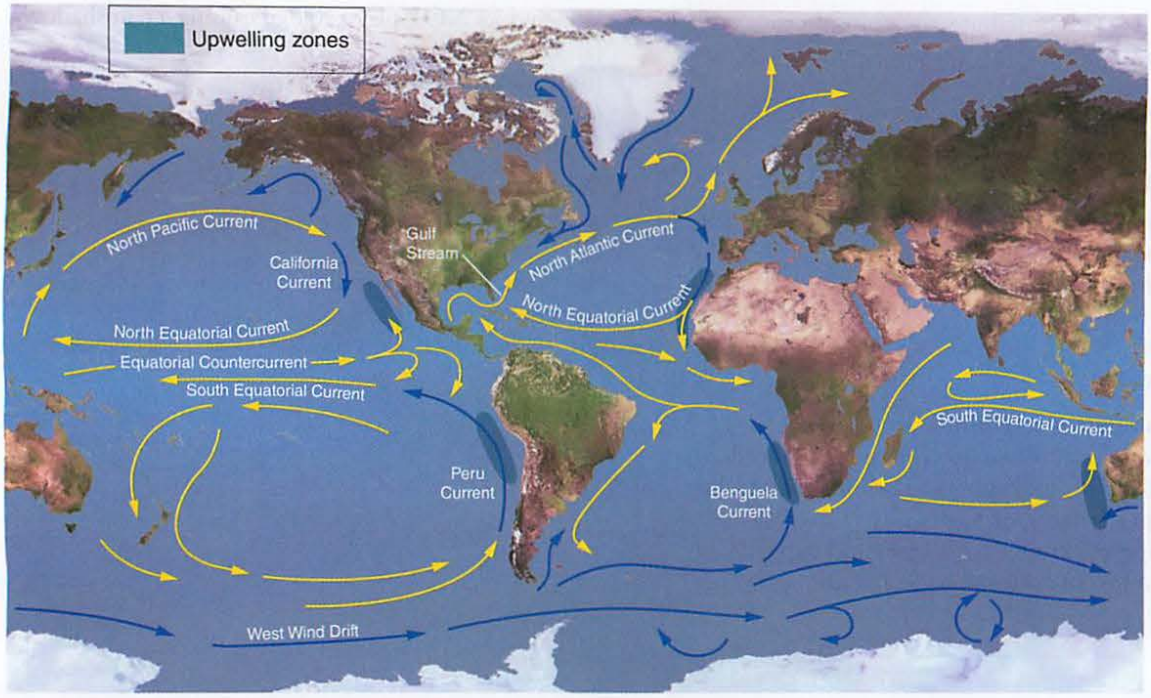


FIGURE 11.1 Oceanic circulation patterns. Oceanic circulation patterns are the result of differential heating, gravity, prevailing winds, the Coriolis effect, and the locations of continents. Each of the five major ocean basins contains a gyre driven by the trade winds in the tropics and the westerlies at mid-latitudes. The result is a clockwise circulation pattern in the Northern Hemisphere and a counterclockwise circulation pattern in the Southern Hemisphere. Along the west coasts of many continents, currents diverge and cause the upwelling of deeper and more fertile water.

ocean. In this section, we will examine the major ocean currents that occur near the oceans and then consider currents that mix the surface water with much deeper water.

Ocean currents are driven by a combination of temperature, gravity, prevailing winds, the Coriolis effect, salinity, and the locations of continents. As we have already observed, the tropics receive the most direct sunlight throughout the year, which generally makes tropical waters warm. Warm water, like warm air, expands and rises. This process raises the tropical water surface about 8 cm (3 inches) higher than mid-latitude waters. While this difference might seem trivial, the slight slope is sufficient for the force of gravity to make water flow away from the equator. As we will see, this movement away from the equator due to gravity combines with other forces to make the surface waters circulate.

Gyres

As the warm tropical waters are pushed away from the equator by gravity, prevailing wind patterns around the globe also play a role in determining the direction in which ocean surface water moves. In the Northern Hemisphere, for example, the trade winds near the equator push water from the northeast to the southwest. However, the Coriolis effect deflects this wind-driven current so that water actually moves from east to west at the equator. Similarly, when winds in northern mid-latitude regions push water from the southwest to the northeast, the Coriolis effect deflects this current so that water actually moves from west to east. **FIGURE 11.1** shows the overall effect: Ocean surface currents between the equator and the mid-latitudes rotate in a clockwise direction in the Northern Hemisphere and in a counterclockwise direction in the Southern Hemisphere. These large-scale patterns of water circulation that move clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere are called **gyres**.

Gyres redistribute heat in the ocean, just as atmospheric convection currents redistribute heat in the atmosphere. Cold water from the polar regions moves along the west coasts of continents, and the cool air immediately above these waters brings cooler temperatures to the adjacent continents. For example, the California Current, which flows south from the North Pacific along the coast of California, causes coastal areas of California to have cooler temperatures than areas at similar latitudes on the east coast of the United States. Similarly, warm water from the tropics moves along the east coasts of continents, and the warm air immediately above these waters causes warmer temperatures on land.

Gyre A large-scale pattern of water circulation that moves clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Upwelling

Ocean currents also help explain why some regions of the ocean support highly productive ecosystems. Along the west coasts of most continents, for

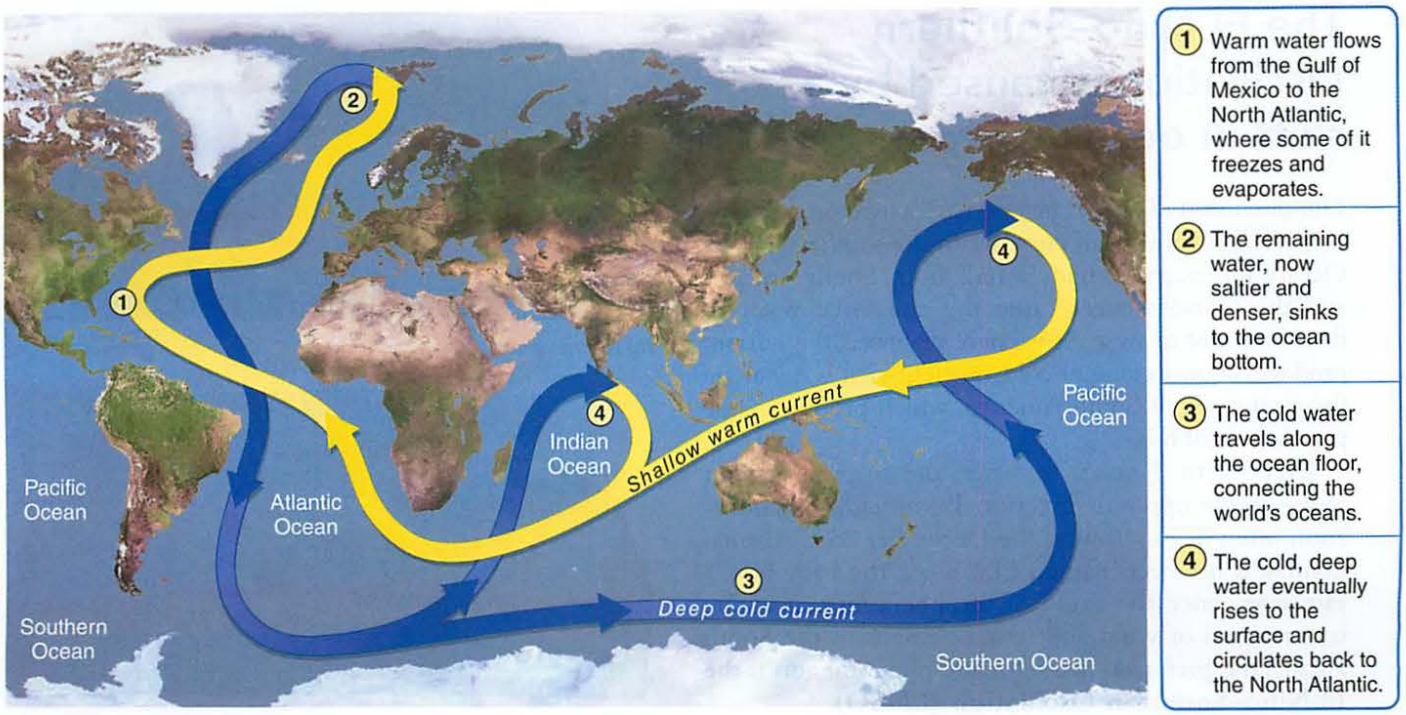


FIGURE 11.2 Thermohaline circulation. The sinking of dense, salty water in the North Atlantic drives a deep, cold current that moves slowly around the world.

example, the surface currents diverge, or separate from one another, causing deeper waters to rise and replace the water that has moved away. This upward movement of water toward the surface, shown as dark blue regions in Figure 11.1, is called **upwelling**. The deep waters bring with them nutrients from the ocean bottom that support large populations of producers. The producers, in turn, support large populations of fish that have long been important to commercial fisheries.

Deep ocean currents circulate ocean water over long time periods

Another oceanic circulation pattern, **thermohaline circulation**, drives the mixing of surface water and deep water. This process is crucial for moving heat and nutrients around the globe. Thermohaline circulation appears to be driven by surface waters that contain unusually large amounts of salt. As Figure 11.1 shows, warm currents flow from the Gulf of Mexico to the very cold North Atlantic. Some of this water freezes or evaporates, and the salt that remains behind increases the salt concentration of the water. This cold, salty water is relatively dense, so it sinks to the bottom of the ocean, mixing with deeper ocean waters. Two processes—the sinking of cold, salty water at high latitudes and the rising of warm water near the equator—create the movement necessary to drive a deep, cold current that slowly moves past Antarctica and northward to the northern Pacific Ocean, where it returns to the surface and then makes its way back to the Gulf of Mexico. This global round trip, shown in **FIGURE 11.2**, can take hundreds of years to complete. As you can see in the figure, thermohaline circulation helps to mix the water of all the oceans.

Ocean currents associated with thermohaline circulation affect the temperature of nearby landmasses much as the major gyres affect surface waters. For example, the ocean current known as the Gulf Stream originates in the tropics near the Gulf of Mexico and flows toward western Europe. This movement of warm tropical waters brings warmer temperatures to latitudes that would otherwise be much colder. For instance, England's average winter temperature is 20°C (36°F) warmer than that of Newfoundland, Canada, which is located at a similar latitude but receives cold ocean currents from the North Atlantic.

Scientists are concerned that global warming could affect thermohaline circulation. If increased air temperatures accelerate the melting of glaciers in the Northern Hemisphere, the waters of the North Atlantic could become less salty and thus less likely to sink. Such a change could potentially shut down thermohaline circulation and stop the transport of warm water to western Europe, making it a much colder place.

Upwelling The upward movement of ocean water toward the surface as a result of diverging currents.

Thermohaline circulation An oceanic circulation pattern that drives the mixing of surface water and deep water.

The El Niño–Southern Oscillation is caused by a shift in ocean currents

Our discussion of ocean currents has focused on the commonly occurring ocean currents. In the southern Pacific Ocean, for example, trade winds from South America and the Coriolis effect cause the equatorial water to flow from east to west. As we have discussed, this current produces an upwelling of cold, nutrient-rich water along the west coast of South America, which produces large populations of fish.

Every 3 to 7 years, however, the tropical current moves in the opposite direction. Because this phenomenon often begins around the December 25 Christmas holiday, it has been named El Niño ("the baby boy"). However, since the cause of the phenomenon is due to a reversal of wind and water currents in the South Pacific, the preferred name for the phenomenon is the **El Niño–Southern Oscillation (ENSO)**.

AP® Exam Tip

You should know when El Niño occurs, as well as the implications of this phenomenon. ●

FIGURE 11.3 shows this process in action. First, the trade winds that normally blow from South America and push the surface waters to the west weaken or reverse direction. This change in the wind allows warm equatorial water from the western Pacific to move eastward toward the west coast of South America. The movement of warm water and air toward South America suppresses upwelling off the coast of Peru. The effect can last from a few weeks to a few years.

Because ocean currents are so important to global climates, the ENSO has several consequences. As we have noted, it reduces the upwelling off the South American coast, which decreases productivity and dramatically reduces fish populations. It also has widespread effects around the world, including cooler and wetter conditions in the southeastern United States and unusually dry weather in southern Africa and Southeast Asia. Such changes can have major impacts of crop production, with some ENSO events leading to poor crop yields and thousands of human deaths in developing countries. The ENSO event that occurred during 2015-2016 was the most severe ENSO in 30 years. Scientists estimate that nearly 100 million people experienced food shortages as a result.

El Niño–Southern Oscillation (ENSO) A reversal of wind and water currents in the South Pacific.

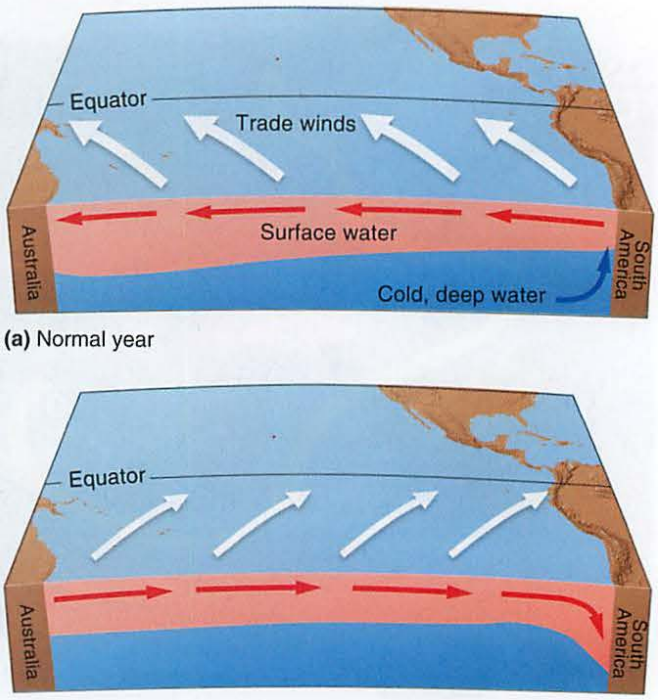


FIGURE 11.3 The El Niño–Southern Oscillation. (a) In a normal year, trade winds push warm surface waters away from the coast of South America and promote the upwelling of water from the ocean bottom. (b) In an El Niño year, trade winds weaken or reverse direction, so warm waters build up along the west coast of Peru.

MODULE 11

AP® Review

Preparing for the AP® Exam

In this module, we have learned that the circulation of surface ocean currents and deep ocean currents is driven by the unequal heating of Earth, air currents, Coriolis forces, and differences in salt concentrations. These currents help to transport heat to different regions of the world and therefore help determine the climates around the globe. The disruption of these currents—due to the ENSO, and potentially because of glacier melting—can have major impacts on these climates. In the next module, we will examine how differences in climate help to determine the plants and animals that live in different parts of the world.

AP® Practice Questions

Choose the best answer for the following.

1. Which does NOT drive ocean currents?
   (a) salinity
   (b) prevailing winds
   (c) temperature
   (d) precipitation
2. High productivity and nutrient availability in the ocean occurs in areas with
   (a) gyres.
   (b) upwelling.
   (c) warm waters.
   (d) prevailing westerlies.
3. Climate change could potentially disrupt which phenomenon?
   (a) El Niño–Southern Oscillation (ENSO)
   (b) thermohaline circulation
   (c) upwelling off the coasts of Australia and New Zealand
   (d) the polar current along Antarctica
4. Which is NOT true of an El Niño–Southern Oscillation (ENSO) event?
   (a) It causes increased upwelling on the west coast of South America.
   (b) It causes wetter conditions in the southern United States.
   (c) It includes a reversal in tropical ocean currents.
   (d) It often begins near Christmas.
5. Gyres do all of the following EXCEPT
   (a) redistribute heat in the ocean.
   (b) result from the Coriolis effect.
   (c) redistribute nutrients from the deep ocean.
   (d) affect the temperatures of coastal areas.

MODULE 12

Terrestrial Biomes

Climate affects the distribution of species around the globe. For example, only species that are well adapted to hot and dry conditions can survive in deserts. A very different set of organisms survives in cold, snowy places. In this module, we will examine how differences in climate help determine the species of plants and animals that live in each region and how scientists categorize these regions.

Learning Goals

After reading this module you should be able to

- explain how we define terrestrial biomes.
- interpret climate diagrams.
- identify the nine terrestrial biomes.

Terrestrial biomes are defined by the dominant plant growth forms

Scientists have long recognized that organisms possess distinct growth forms, many of which represent adaptations to local temperature and precipitation patterns. For example, if we were to examine the plants from all the deserts of the world, we would find many cactus-like species. Plants that look like cacti in North American deserts are indeed members of the cactus family, but those in the Kalahari Desert are members of the euphorb family. These two distantly related families of plants look similar because they have evolved similar adaptations to hot, dry environments—including the ability to store large amounts of water in their tissues and a waxy coating to reduce water loss (**FIGURE 12.1**).



FIGURE 12.1 Similar growth forms. Cacti and euphorbs are not closely related, but they have evolved many similar adaptations that allow them to live in hot, dry environments. (a) Organ pipe cactus (*Stenocereus thurberi*) in Arizona. (b) Euphorbia (*E. damarana*) in Namibia. *(a: Dhoxax/Shutterstock; b: Patti Murray/Earth Scenes/Animals Animals)*

Despite these common adaptations to desert conditions, these two plant families have distinctive flowers and spines, and only the euphorb family produces a milky sap. These differences help to confirm that while the two groups may look similar, genetically they are not closely related. Instead, exposure to similar selective pressures over long periods of time has favored the evolution of many similar adaptations. We will discuss this in more detail in Chapter 5. As a result, scientists can categorize terrestrial regions of the world into **terrestrial biomes**, which are geographical regions that each have a particular combination of average annual temperature and precipitation and contain distinctive plant growth forms that are adapted to that climate. In the next module we will examine **aquatic biomes**, which are categorized by particular combinations of salinity, depth, and water flow. **FIGURE 12.2** shows the range of terrestrial biomes on Earth in the context of precipitation and temperature. For example, boreal and tundra biomes have average annual temperatures below 5°C (41°F), whereas temperate biomes have average annual temperatures between 5°C and 20°C (68°F), and tropical biomes have average annual temperatures above 20°C. Within each of these temperature ranges, we can observe a wide range of precipitation. **FIGURE 12.3** shows the distribution of biomes around the world.

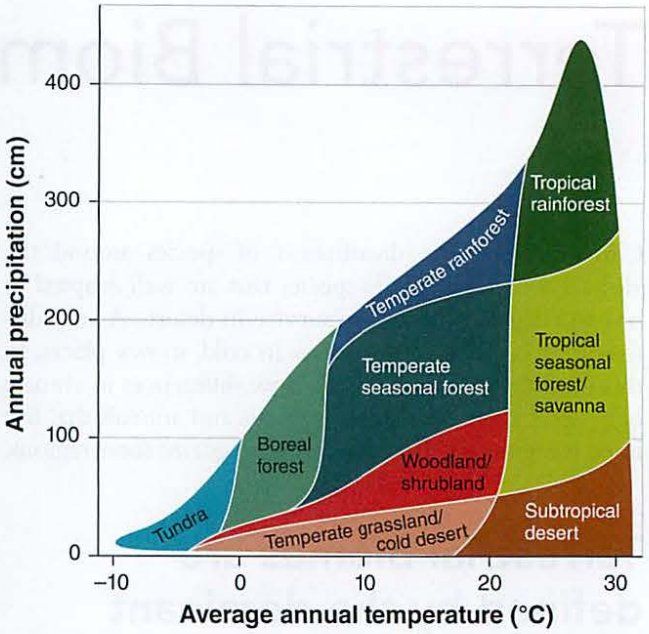


FIGURE 12.2 Locations of the world's biomes. Tundra and boreal biomes generally exist when the average annual temperature is less than 5°C (41°F). In contrast, temperate biomes exist in regions that experience average annual temperatures between 5°C and 20°C (41°F and 68°F). Tropical biomes exist in regions that experience average annual temperatures above 20°C.

Terrestrial biome A geographic region categorized by a particular combination of average annual temperature, annual precipitation, and distinctive plant growth forms on land.

Aquatic biome An aquatic region characterized by a particular combination of salinity, depth, and water flow.

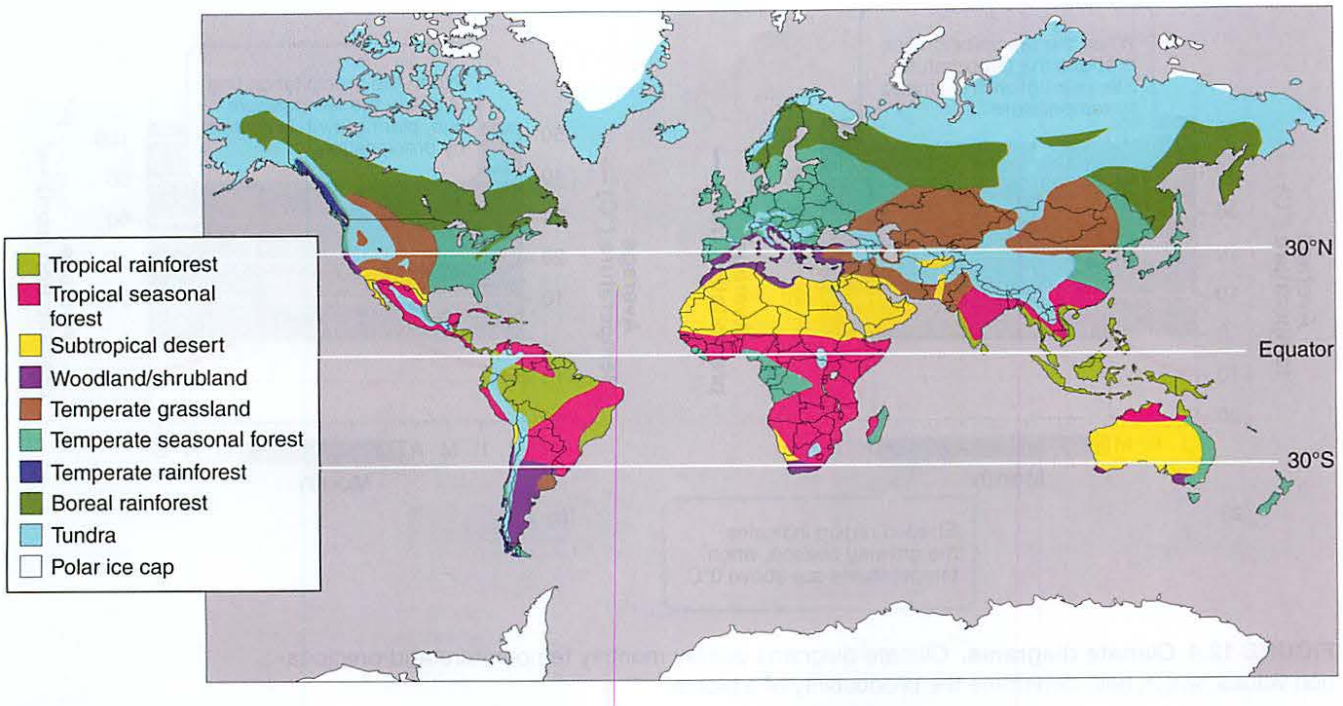


FIGURE 12.3 Biomes. Biomes are categorized by particular combinations of average annual temperature and annual precipitation.

AP® Exam Tip

Students often confuse biomes with habitats, so make sure that you can differentiate between the two. ●

Note that although terrestrial biomes are categorized by plant growth forms, the animal species living in different biomes are often quite distinctive as well. For example, rodents inhabiting deserts around the world have a number of adaptations for hot, dry climates, including highly efficient kidneys that allow very little water loss through urination. For both plants and animals, biomes refer to large geographical areas that are home to large numbers of species. In contrast, a **habitat** is an area where a particular species lives in nature. A habitat is a subset of a biome. For example, the forests of the northeastern United States represent a biome, but this biome contains multiple terrestrial habitats including agricultural fields, abandoned fields, young forests with sapling trees, and mature forests.

Climate diagrams illustrate patterns of annual temperature and precipitation

Climate diagrams, such as those shown in FIGURE 12.4 on page 128, are a helpful way to visualize regional patterns of temperature and precipitation. By graphing average monthly temperature and precipitation, these diagrams illustrate how the conditions in a biome vary during a typical year. They also indicate when the temperature is warm enough for plants to grow—that is, the months when it is above 0°C (32°F), known as the growing season. In Figure 12.4a, we can see that the growing season is mid-March through mid-October.

In addition to the growing season, climate diagrams can show the relationship between precipitation, temperature, and plant growth. For every 10°C (18°F) temperature increase, plants need 20 mm (0.8 inches) of additional precipitation each month to supply the extra water demand that warmer temperatures cause. As a result, plant growth can be limited either by temperature or by precipitation. In Figure 12.4a, the precipitation line is above the temperature line during all months. This means that water supply of plants exceeds the water demand, so plant growth is more constrained by temperature than by precipitation.

In Figure 12.4b, we see a different scenario. When the precipitation line intersects the temperature line, the amount of precipitation available to plants equals the amount of water lost by plants through evapotranspiration. At any point where the precipitation line is below the temperature line, water demand exceeds supply. In this situation, plant growth will be constrained more by precipitation than by temperature.

Climate diagrams also help us understand how humans use different biomes. For example, areas of the world that have warm temperatures, long growing seasons, and abundant rainfall are generally highly productive and therefore are well suited to growing many crops. Warm regions that have less abundant precipitation are suitable for growing

Habitat An area where a particular species lives in nature.

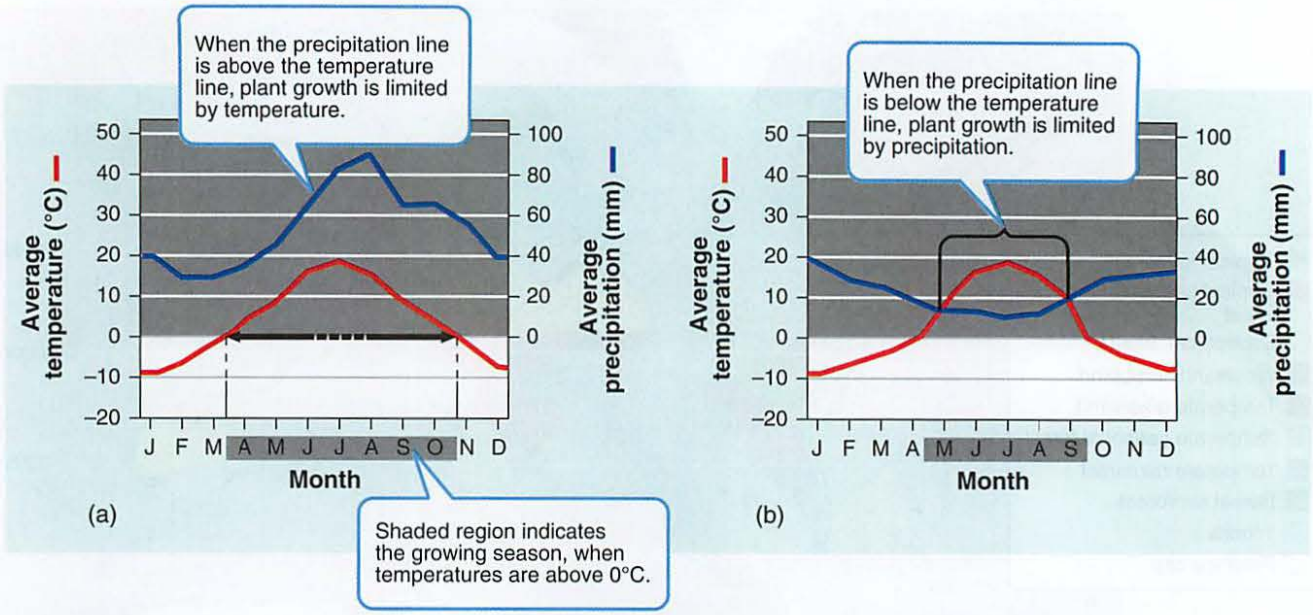


FIGURE 12.4 Climate diagrams. Climate diagrams display monthly temperature and precipitation values, which help determine the productivity of a biome.

grains such as wheat and for grazing domesticated animals, including cattle and sheep. Colder regions are often best used to grow forests that will be harvested for lumber.

Terrestrial biomes range from tundra to tropical forests

We can divide terrestrial biomes into three categories: tundra and boreal forest, temperate, and tropical. These three categories contain a total of nine biomes. We will examine each of these biomes in turn, looking at temperature and precipitation patterns, geographic distribution, and typical plant and animal growth forms.

Tundra

The **tundra**, shown in **FIGURE 12.5**, is a cold and treeless biome, with low-growing vegetation. In winter, the soil is completely frozen. Arctic tundra is found in the northernmost regions of the Northern Hemisphere in Russia, Canada, Scandinavia, and Alaska. Antarctic tundra is found along the edges of Antarctica and on nearby islands. At lower latitudes, alpine tundra can be found on high mountains, where high winds and low temperatures prevent trees from growing.

Tundra A cold and treeless biome with low-growing vegetation.

Permafrost An impermeable, permanently frozen layer of soil.

Boreal forest A forest biome made up primarily of coniferous evergreen trees that can tolerate cold winters and short growing seasons.

The growing season in the tundra is very short, usually only about 4 months during summer, when the polar region is tilted toward the Sun and the days are very long. During this time the upper layer of soil thaws, creating pools of standing water that are ideal habitat for mosquitoes and other insects. The underlying subsoil, known as **permafrost**, is an impermeable, permanently frozen layer that prevents water from draining and roots from penetrating. Permafrost, combined with the cold temperatures and a short growing season, prevents deep-rooted plants such as trees from living in the tundra.

While the tundra receives little precipitation, there is enough to support some plant growth. The characteristic plants of this biome, such as small woody shrubs, mosses, heaths, and lichens, can grow in shallow, waterlogged soil and can survive short growing seasons and bitterly cold winters. At these cold temperatures, chemical reactions occur slowly, and as a result, dead plants and animals decompose slowly. This slow rate of decomposition results in the accumulation of organic matter in the soil over time with relatively low levels of soil nutrients. Common animals in the Arctic tundra include muskoxen (*Ovibos moschatus*), Arctic foxes (*Vulpes lagopus*), and polar bears (*Ursus maritimus*). The major human impact on the tundra biome is the threat of warming global temperatures melting the permafrost, which would then decompose at a faster rate than usual and such decomposition would release additional greenhouse gases. We will discuss this in more detail in Chapter 19.

Boreal Forest

The **boreal forest** biome, shown in **FIGURE 12.6**, consists primarily of coniferous (cone-bearing) evergreen trees that can tolerate cold winters and short growing seasons. Boreal forests are sometimes called taiga.

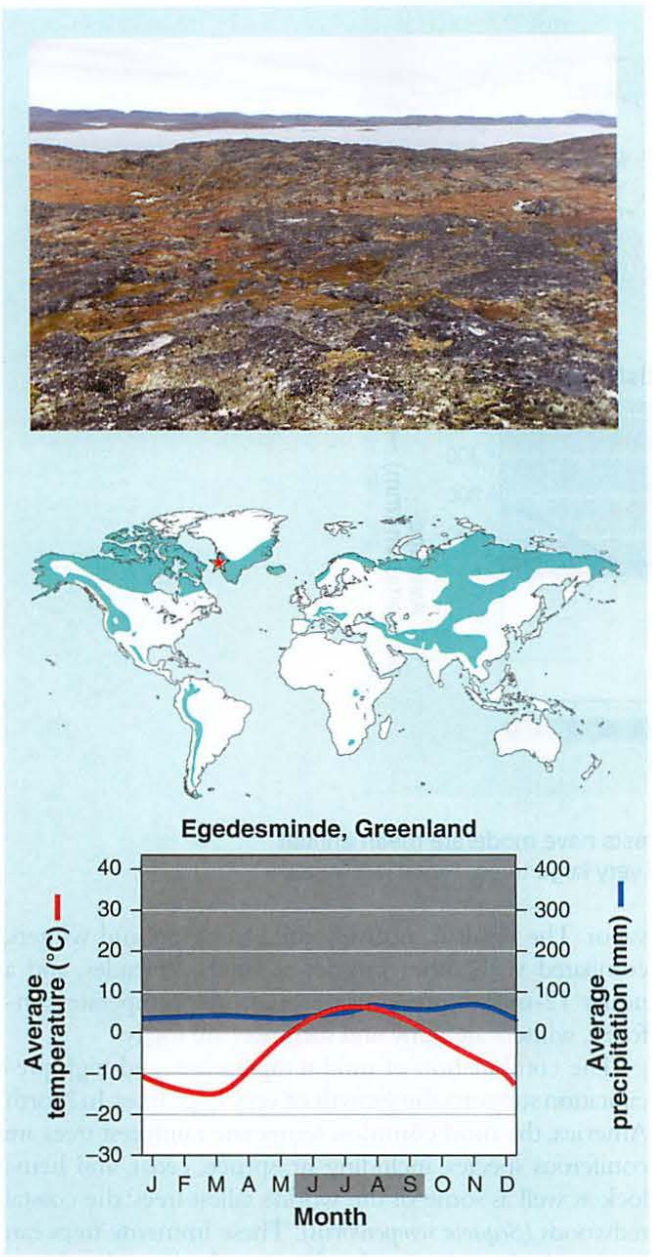


FIGURE 12.5 Tundra biome. The tundra is cold and treeless, with low-growing vegetation. *(Panther Media GmbH/Alamy)*

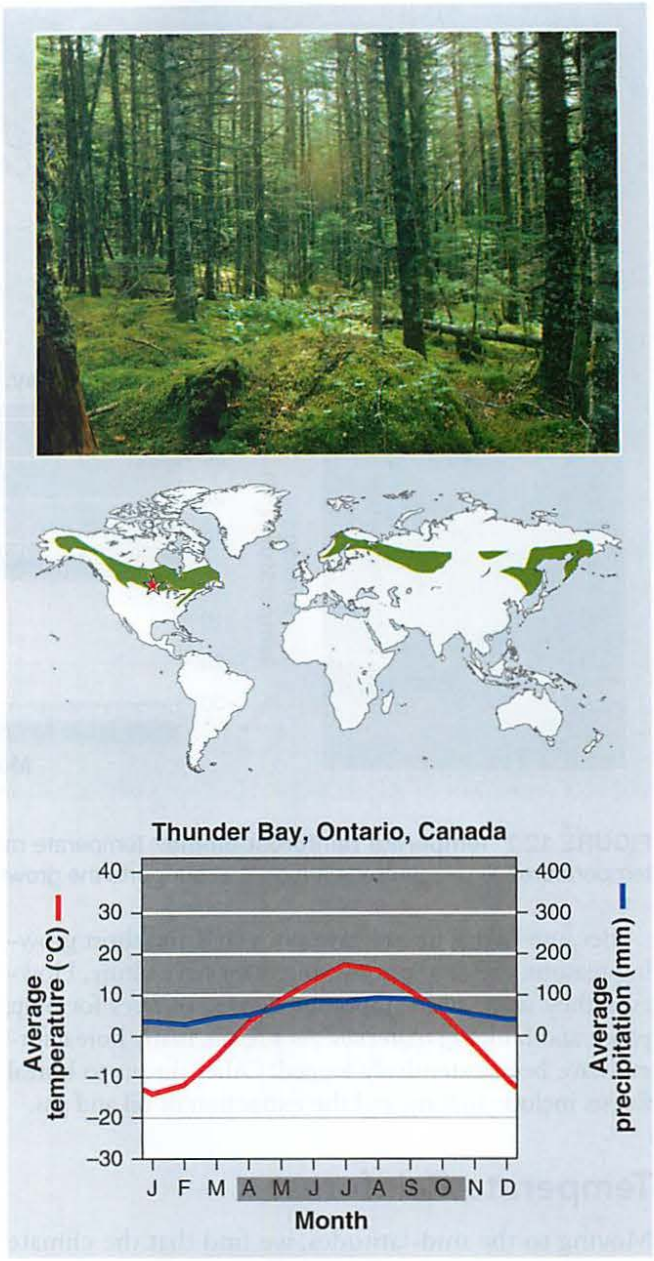


FIGURE 12.6 Boreal forest biome. Boreal forests are made up primarily of coniferous evergreen trees that can tolerate cold winters and short growing seasons. *(Bill Brooks/Alamy)*

Evergreen trees appear green year-round because they drop only a fraction of their needles each year. Boreal forests are found between about 50° N and 60° N in Europe, Russia, and North America. This subarctic biome has a very cold climate, and plant growth is more constrained by temperature than by precipitation.

As in the tundra, cold temperatures and relatively low precipitation make decomposition in boreal forests a slow process. In addition, the waxy needles of evergreen trees contain compounds that are resistant to decomposition. As a result of the slow rate of decomposition and the low nutrient content of the needles, boreal forest soils are covered in a thick layer of organic material, but are poor in nutrients.

The climate characteristics of boreal forests—cold temperatures, low precipitation, and nutrient-poor soil—determine the species of plants that can survive in them. In addition to coniferous trees such as pine, spruce, and fir, some deciduous trees, such as birch, maple, and aspen, can also be found in this biome. The needles of coniferous trees can tolerate below-freezing conditions, but the deciduous trees drop all their leaves in autumn before the subfreezing temperatures of winter can damage them. When the weather warms, the deciduous trees produce new leaves and grow rapidly. Common animal species include beavers (*Castor Canadensis*), brown bears (*Ursus arctos*), and wolverines (*Gulo gulo*).

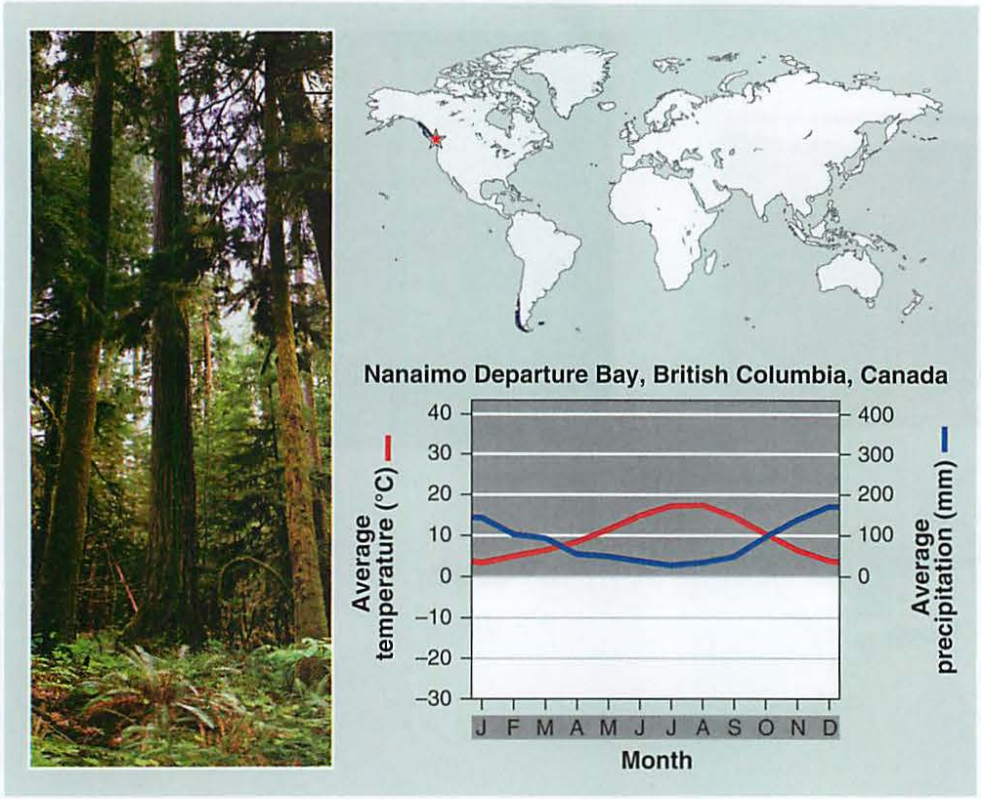


FIGURE 12.7 Temperate rainforest biome. Temperate rainforests have moderate mean annual temperatures and high precipitation that supports the growth of very large trees. *(BGSmith/Shutterstock)*

Because boreal forests have poor soils and short growing seasons, they are poorly suited for agriculture. However, they serve as an important source of trees for pulp, paper, and building materials. As a result, many boreal forests have been extensively logged. Other threats to boreal forests include mining and the extraction of oil and gas.

Temperate Rainforest

Moving to the mid-latitudes, we find that the climate is more temperate, with average annual temperatures between 5°C and 20°C (41°F and 68°F). A range of temperate biomes exists in this area including temperate rainforest, temperate seasonal forest, woodland/shrubland, and temperate grassland/cold desert.

Moderate temperatures and high precipitation typify the **temperate rainforest** biome, shown in **FIGURE 12.7**. The temperate rainforest is a coastal biome and can be found in relatively narrow areas around the world. Temperate rainforests exist along the west coast of North America from northern California to Alaska, in southern Chile, on the east coast of Australia and in neighboring Tasmania, and on the west coast of New Zealand. Ocean currents along these coasts help to moderate temperature fluctuations, and ocean water provides a source of water vapor. The result is relatively mild summers and winters, compared with other biomes at similar latitudes, and a nearly 12-month growing season. In the temperate rainforest, winters are rainy and summers are foggy.

Temperate rainforest A coastal biome typified by moderate temperatures and high precipitation.

The combination of mild temperatures and high precipitation supports the growth of very large trees. In North America, the most common temperate rainforest trees are coniferous species, including fir, spruce, cedar, and hemlock as well as some of the world's tallest trees: the coastal redwoods (*Sequoia sempervirens*). These immense trees can live hundreds to thousands of years and achieve heights of 90 m (295 feet) and diameters of 8 m (26 feet). Because many of these large tree species are attractive sources of lumber, much of this biome has been logged and subsequently converted into single-species tree plantations.

As we have already seen, coniferous trees produce needles that are slow to decompose. The relatively cool temperatures in the temperate rainforest also favor slow decomposition, although it is not nearly as slow as in boreal forest and tundra. The nutrients released are rapidly taken up by the trees or leached down through the soil by the abundant rainfall, which leaves the soil low in nutrients. Ferns and mosses, which can survive in nutrient-poor soil, are commonly found living under the enormous trees. Animals that are characteristic of the temperate rainforest in North America include the black-tailed deer (*Odocoileus hemionus columbianus*), the Pacific giant salamander (*Dicamptodon ensatus*), and the Pacific treefrog (*Pseudacris regilla*).

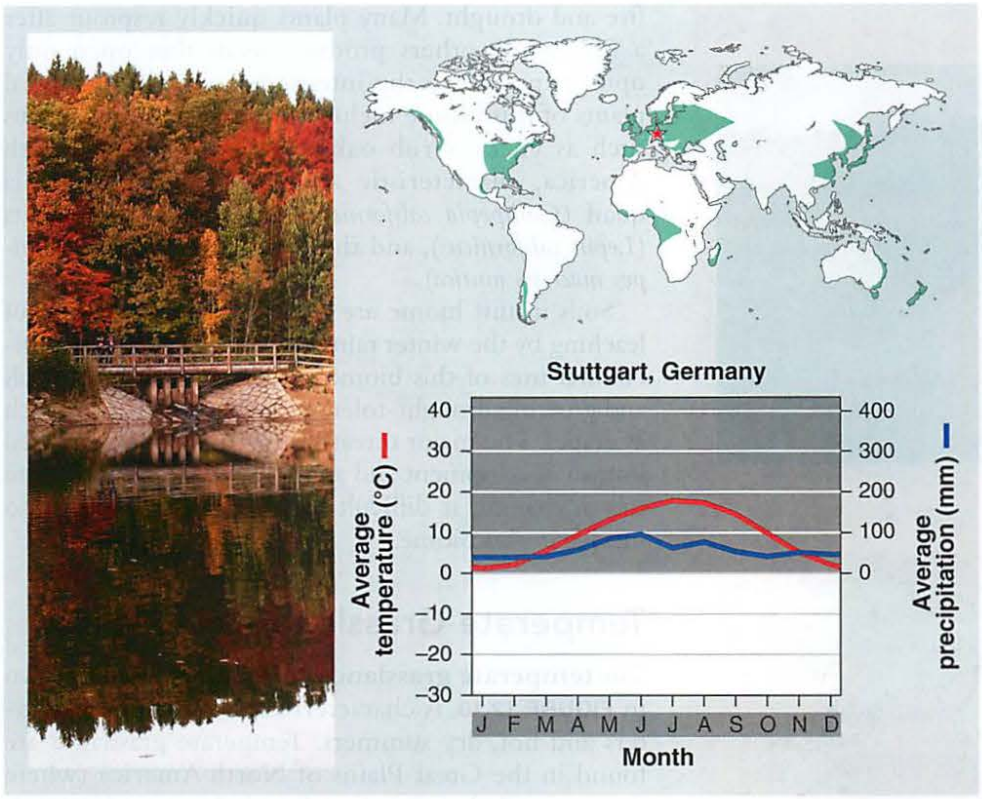


FIGURE 12.8 Temperate seasonal forest biome. Temperate seasonal forest biomes have moderate mean annual temperatures and moderate amounts of precipitation that support broadleaf deciduous trees such as beech, maple, oak, and hickory. *(Ursula Sander/Getty Images)*

Temperate Seasonal Forest

The **temperate seasonal forest** biome, shown in **FIGURE 12.8**, experiences warm summers and cold winters with over 1 m (39 inches) of annual precipitation. It is found in the eastern United States, Japan, China, Europe, Chile, and eastern Australia. Away from the moderating influence of the ocean, these forests experience much warmer summers and colder winters than temperate rainforests. They are dominated by broadleaf deciduous trees such as beech, maple, oak, and hickory, although some coniferous tree species may also be present. Because of the predominance of deciduous trees, these forests are also called temperate deciduous forests.

The warm summer temperatures in temperate seasonal forests favor rapid decomposition. Because the leaves shed by broadleaf trees are more readily decomposed than the needles of coniferous trees, the soils of temperate seasonal forests generally contain more nutrients than those of boreal forests. Their higher soil fertility, combined with their longer growing season, means that temperate seasonal forests have greater plant productivity than boreal forests. Common animal species include white-tailed deer (*Odocoileus virginianus*), red foxes (*Vulpes vulpes*), and gray squirrels (*Sciurus carolinensis*).

Because temperate seasonal forests are so productive, they have historically been one of the first biomes to be converted to agriculture on a large scale. When European settlers arrived in North America, they cleared large areas of the eastern forests for agriculture, although much of this has since grown back.

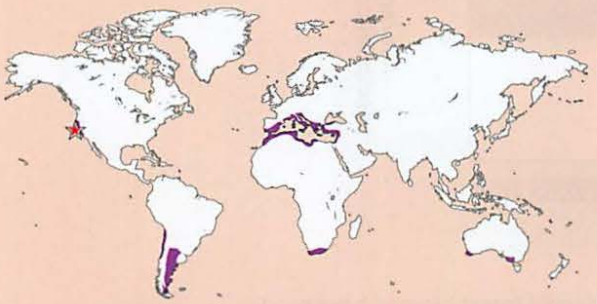
Woodland/Shrubland

The **woodland/shrubland** biome, illustrated in **FIGURE 12.9**, is characterized by hot, dry summers and mild, rainy winters. This biome is found on the coast of southern California (where it is called chaparral), in southern South America (matorral), in southwestern Australia (mallee), in southern Africa (fynbos), and in a large region surrounding the Mediterranean Sea (maquis). There is a 12-month growing season, but plant growth is constrained by high temperatures and low precipitation in summer and by cool temperatures

Temperate seasonal forest A biome with warm summers and cold winters with over 1 m (39 inches) of precipitation annually.

Woodland/shrubland A biome characterized by hot, dry summers and mild, rainy winters.





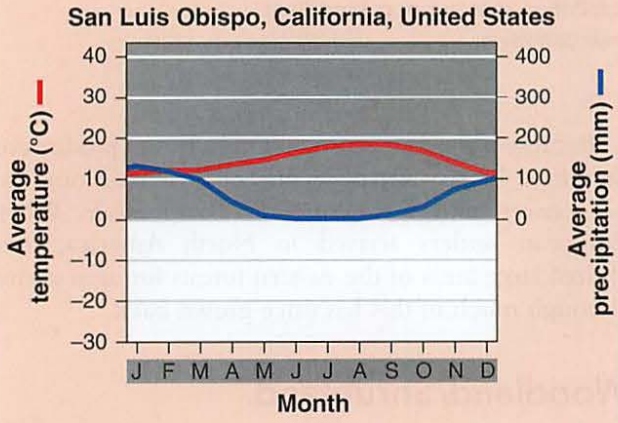


FIGURE 12.9 Woodland/shrubland biome. The woodland/shrubland biome is characterized by hot, dry summers and mild, rainy winters. *(George Rose/Getty Images)*

and higher precipitation in winter. As discussed at the beginning of the chapter, these are the ideal conditions for growing grapes for making wine.

The hot, dry summers of the woodland/shrubland biome favor the natural occurrence of wildfires. Plants of this biome are well adapted to both fire and drought. Many plants quickly resprout after a fire, while others produce seeds that open only upon exposure to the intense heat of a fire. Typical plants of this biome include drought-resistant shrubs such as yucca, scrub oak, and sagebrush. In North America, characteristic animals include California quail (*Callipepla californica*), black-tailed jackrabbits (*Lepus californicus*), and the San Joaquin kit fox (*Vulpes macrotis mutica*).

Soils in this biome are low in nutrients because of leaching by the winter rains. As a result, the major agricultural uses of this biome are for grazing by animals and growing drought-tolerant, deep-rooted crops, such as grapes. The major threats from humans are increased human development and an increased frequency of fire that is making it difficult for many native species to survive in this biome.

Temperate grassland/cold desert A biome characterized by cold, harsh winters, and hot, dry summers.

Temperate Grassland/Cold Desert

The **temperate grassland/cold desert** biome, shown in **FIGURE 12.10**, is characterized by cold, harsh winters and hot, dry summers. Temperate grasslands are found in the Great Plains of North America (where they are called prairies), in South America (pampas), and in central Asia and eastern Europe (steppes). Cold, harsh winters and hot, dry summers characterize this biome. Thus, as in the woodland/shrubland biome, plant growth is constrained by insufficient precipitation in summer and cold temperatures in winter. Fires are common, as the dry and frequently windy conditions fan flames ignited by lightning. Although estimates vary, it is thought that, historically, large wildfires occurred in this biome every few years, sometimes burning as much as 10,000 ha (nearly 25,000 acres) in a single fire.

Typical plants of temperate grasslands include grasses and nonwoody flowering plants. These plants are generally well adapted to wildfires and frequent grazing by animals. Their deep roots store energy to enable quick regrowth. Within this biome, the amount of rainfall determines which plants can survive in a region. In the North American prairies, for example, nearly 1 m (39 inches) of rain falls per year on the eastern edge of the biome, supporting grasses that can grow up to 2.5 m (8 feet) high. Although these tallgrass prairies receive sufficient rainfall for trees to grow, frequent wildfires keep trees from encroaching. In fact, the Native American people are thought to have intentionally kept the eastern prairies free of trees by using controlled burning. To the west, annual precipitation drops to 0.5 m (20 inches), favoring the growth of grasses less than 0.5 m (20 inches) tall. These shortgrass prairies are simply too dry to support trees or tall grasses. Farther west, in the rain shadow of the Rocky Mountains, annual precipitation continues to decline to 0.25 m (10 inches). In this region, the shortgrass prairie gives way to cold desert.

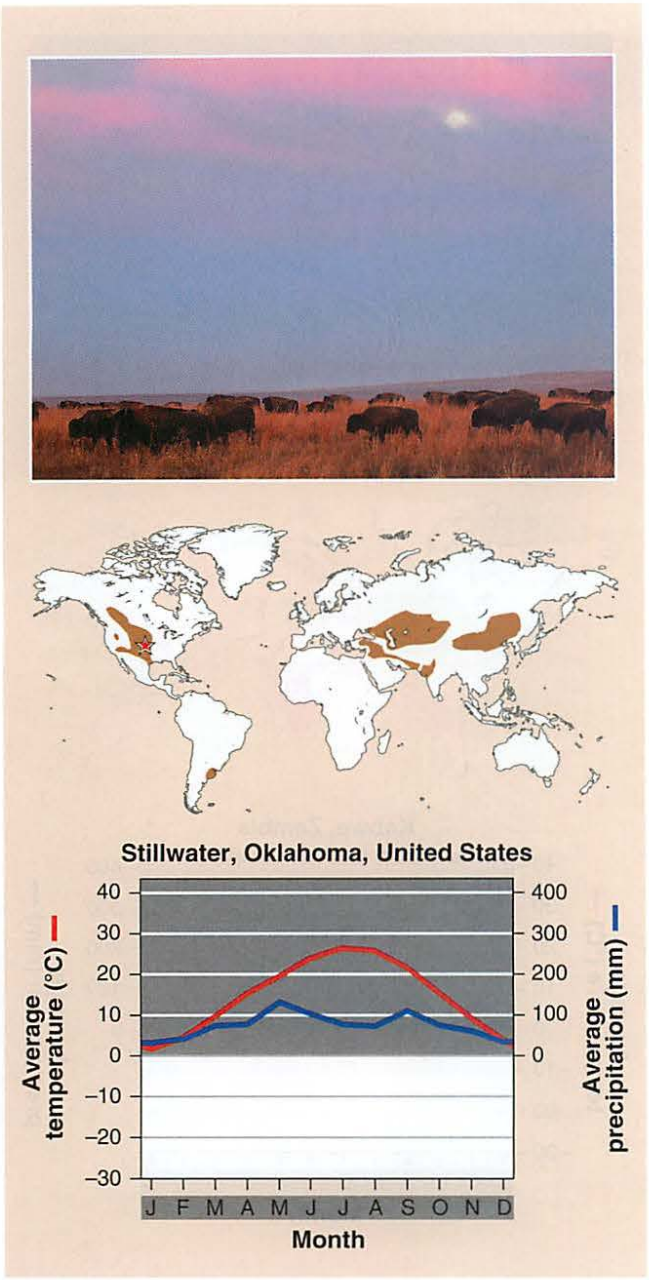


FIGURE 12.10 Temperate grassland/cold desert biome. The temperate grassland/cold desert biome has cold, harsh winters and hot, dry, summers that support grasses and nonwoody flowering plants. *(AP Photo/Brandi Simons)*

Cold deserts, also known as temperate deserts, have even sparser vegetation than shortgrass prairies. Cold deserts are distinct from subtropical deserts in that they have much colder winters and do not support the characteristic plant growth forms of hot deserts, such as cacti and euphorbs. Typical animals of the North American prairie include bison, greater prairie chickens (*Tympanuchus cupido*), and the prairie kingsnake (*Lampropeltis calligaster*).

The combination of a relatively long growing season and rapid decomposition that adds large amounts of nutrients to the soil makes temperate grasslands very productive. More than 98 percent of the tallgrass prairie in the United States has been converted to agriculture, while the less productive shortgrass prairie is predominantly used for growing wheat and grazing cattle.

Tropical Rainforest

In the tropics, average annual temperatures exceed 20°C. Here we find the tropical biomes: tropical rainforests, tropical seasonal forests/savannas, and subtropical deserts.

The **tropical rainforest** biome, shown in **FIGURE 12.11** on page 134, is a warm and wet biome that lies within approximately 20° N and 20° S of the equator. This biome is found in Central and South America, Africa, Southeast Asia, and northeastern Australia. It is also found on large tropical islands, where the oceans provide a constant source of atmospheric water vapor.

Precipitation occurs frequently, although there are seasonal patterns in precipitation that depend on when the ITCZ passes overhead. Because of the warm temperatures and abundant rainfall, productivity is high, and decomposition is extremely rapid. The lush vegetation takes up nutrients quickly, leaving few nutrients to accumulate in the soil. Because of its high productivity, approximately 24,000 ha (59,500 acres) of tropical rainforest are cleared each year for agriculture. However, the high rate of decomposition causes the soils to lose their fertility quickly, so they have relatively little undecomposed organic matter (humus). As a result, farmers growing crops on tropical soils often have to keep moving to newly deforested areas.

Tropical rainforests contain more biodiversity per hectare than any other terrestrial biome. As much as two-thirds of Earth's terrestrial species are found in this biome. These forests have several distinctive layers of vegetation. Large trees form a forest canopy that shades the underlying vegetation. Several layers of successively shorter trees make up the subcanopy, also known as the understory. Attached to the trunks and branches of the trees are epiphytes, plants that hold small pools of water that support small aquatic ecosystems far above the forest floor. Numerous species of woody vines (also called lianas) are rooted in the soil, but climb up the trunks of trees and often into the canopy. Common animals in tropical rainforests around the world include jaguars (*Panthera onca*), orangutans, and red-eyed treefrogs (*Agalychnis callidryas*). The domin-ant human threat to tropical rainforests is deforestation due to expanding forestry and agriculture.

Tropical rainforest A warm and wet biome found between 20° N and 20° S of the equator, with little seasonal temperature variation and high precipitation.

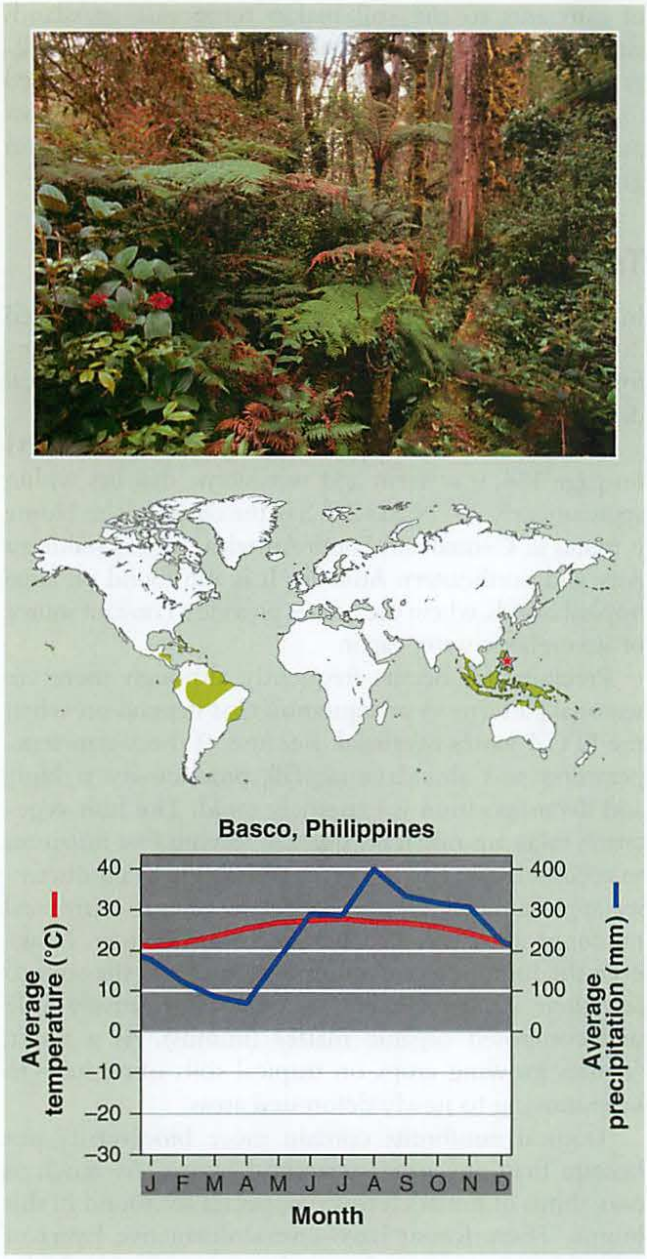


FIGURE 12.11 Tropical rainforest biome. Tropical rainforests are warm and wet, with little seasonal temperature variation. These forests are highly productive with several distinctive layers of vegetation. *(Doug Weschler/Earth Scenes/Animals Animals)*

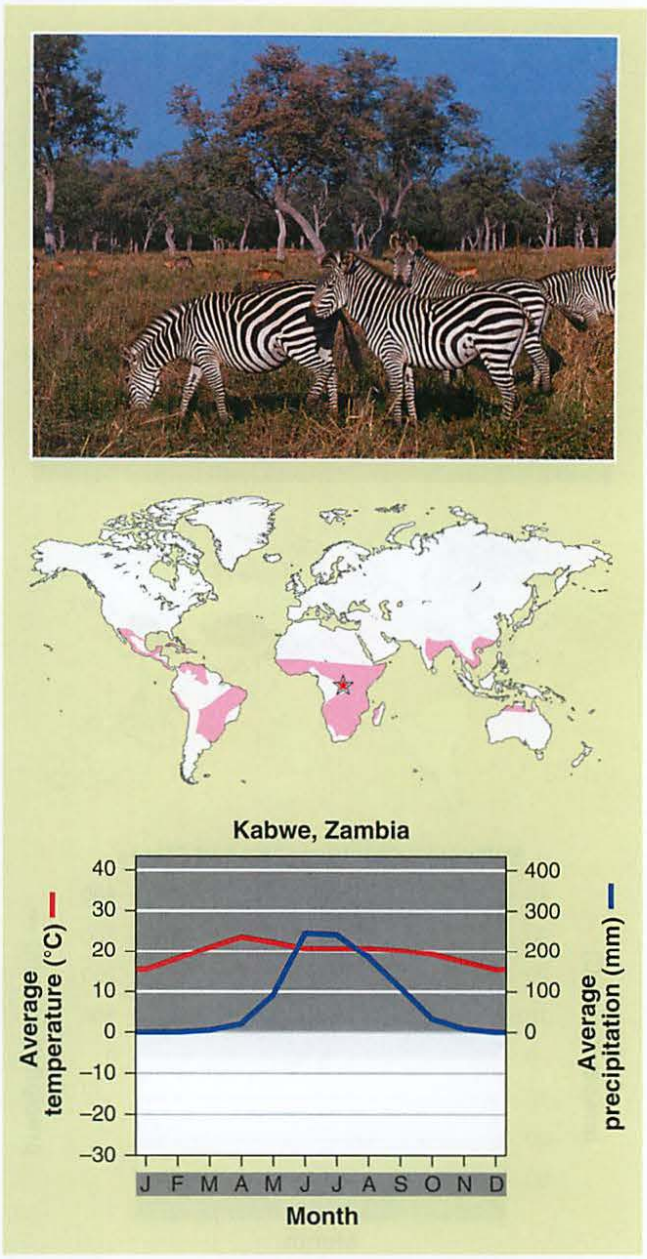


FIGURE 12.12 Tropical seasonal forest/savanna biome. Tropical seasonal forest and savannas have warm temperatures and distinct wet and dry seasons. Vegetation ranges from dense stands of shrubs and trees to relatively open landscapes dominated by grasses and scattered deciduous trees. *(John Warburton-Lee/DanitaDelimont.com)*

Tropical Seasonal Forest/Savanna

The **tropical seasonal forests/savanna** biome, shown in **FIGURE 12.12**, is marked by warm temperatures and distinct wet and dry seasons. This seasonal pattern is caused by the seasonal movement of the ITCZ, which, because it tracks the seasonal movement of the most intense sunlight, passes overhead and drops precipitation only during summer. The trees drop their leaves during the dry season as an adaptation to survive the drought conditions and produce new leaves during the wet season. Thus these forests are also called tropical deciduous forests.

Tropical seasonal forest/savanna A biome marked by warm temperatures and distinct wet and dry seasons.

Tropical seasonal forests are common in much of Central America, on the Atlantic coast of South America, in southern Asia, in northwestern Australia, and in sub-Saharan Africa. Areas with moderately long dry seasons support dense stands of shrubs and trees. In areas with the longest dry seasons, the tropical seasonal climate leads to the formation of savannas, relatively open landscapes dominated by grasses and scattered deciduous trees. Common plants in this biome include acacia and baobab trees. Grazing and fire discourage the growth of many smaller woody plants and keep the savanna landscape open. The presence of trees and a warmer average annual temperature distinguish savannas from grasslands.

The warm temperatures of the tropical seasonal forest/savanna biome promote decomposition, but the low amounts of precipitation constrain plants from using the soil nutrients that are released. As a result, the soils of this biome are fairly fertile and can be farmed. Their fertility has resulted in the conversion of large areas of tropical seasonal forest and savanna into agricultural fields and grazing lands. For example, over 99 percent of the tropical seasonal forest of Pacific Central America and the Atlantic coast of South America has been converted to human uses, including agriculture and grazing. Common animals in this biome from around the world include large grazing animals such as several species of gazelles and zebras (*Equus* spp.), and large predators such as African lions and cheetahs.

Subtropical Desert

The **subtropical desert** biome, shown in **FIGURE 12.13**, is located at roughly 30° N and 30° S, and is characterized by hot temperatures, extremely dry conditions, and sparse vegetation. Also known as hot deserts, this biome includes the Mojave Desert in the southwestern United States, the Sahara in Africa, the Arabian Desert of the Middle East, and the Great Victoria Desert of Australia. Cacti, euphorbs, and succulent plants are well adapted to this biome. To prevent water loss, the leaves of desert plants may be small, nonexistent, or modified into spines, and the outer layer of the plant is thick, with few pores for water and air exchange. Most photosynthesis occurs along the plant stem, which stores water so that photosynthesis can continue even during very dry periods. To protect themselves from herbivores, desert plants have developed defense mechanisms such as spines to discourage grazing. Desert-adapted animals around the world include multiple species of tortoises, camels, and roadrunners.

When rain does fall, the desert landscape is transformed. Annual plants—those that live for only a few months, reproduce, and die—grow rapidly during periods of rain. In contrast, perennial plants—those that live for many years—experience spurts of growth when it rains, but then exhibit little growth during the rest of the year. The slow overall growth of perennial plants in subtropical deserts makes them particularly vulnerable to disturbance, and they have long recovery times. The major threats to this biome include climate change and the draining of underground water for human use.

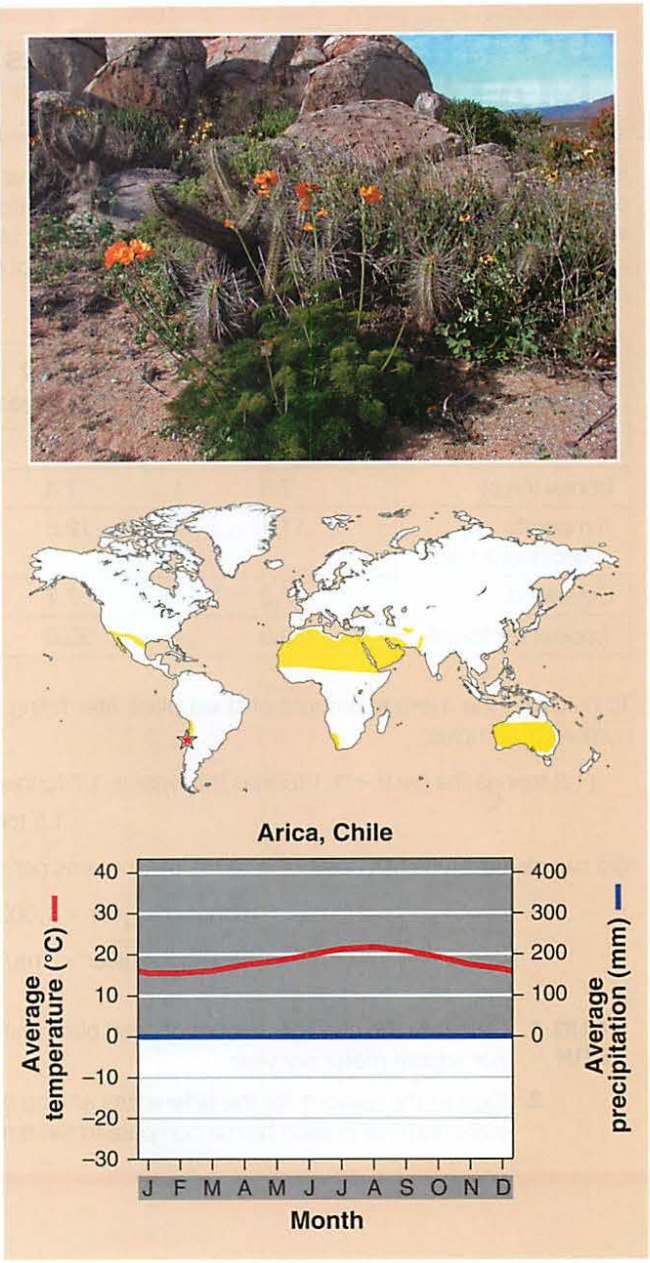


FIGURE 12.13 Subtropical desert biome. Subtropical deserts have hot temperatures, extremely dry conditions, and sparse vegetation. *(Topham/The Image Works)*

Subtropical desert A biome prevailing at approximately 30° N and 30° S, with hot temperatures, extremely dry conditions, and sparse vegetation.

DO THE MATH Organic Matter Inputs Among Terrestrial Biomes

Preparing for the AP® Exam

In our discussion of the terrestrial biomes, we have seen that each biome differs in the productivity of plants and in the amount of organic matter left to decompose in the soil. To get a better understanding of these differences, scientists set out containers in different biomes to determine exactly how much dead plant material actually falls to the ground. Using their data, shown in the table below, we can calculate the average amount of dead plant material falling in each biome in units of metric tonnes per hectare per year.

Biome	Sample 1 (tonnes/ha/year)	Sample 2 (tonnes/ha/year)	Sample 3 (tonnes/ha/year)	Sample 4 (tonnes/ha/year)	Sample 5 (tonnes/ha/year)
Tundra	1.3	1.1	1.7	1.5	1.9
Boreal forest	7.5	7.4	7.6	7.5	7.5
Temperate deciduous forest	11.1	12.5	10.4	9.9	13.2
Grassland	7.3	7.7	7.4	7.6	7.5
Tropical rainforest	29.0	30.0	31.0	35.0	25.0

To calculate the average amount of dead plant litter falling in the tundra biomes, we sum the five values and divide by the number of samples

$$(1.3 \text{ tonnes/ha/year} + 1.1 \text{ tonnes/ha/year} + 1.7 \text{ tonnes/ha/year} + 1.5 \text{ tonnes/ha/year} + 1.9 \text{ tonnes/ha/year}) \div 5$$
$$= 1.5 \text{ tonnes/ha/year}$$

We can also express this number in terms of kilograms per square meter per year:

$$1.5 \text{ tonnes/ha/year} \times 1{,}000 \text{ kg/tonnes} = 1{,}500 \text{ kg/ha/year}$$
$$1{,}500 \text{ kg/ha/year} \times 1\text{ha}/10{,}000 \text{ m}^2 = 0.15 \text{ kg/m}^2\text{/year}$$

YOUR TURN

1. Calculate the average amount of dead plant material that fall in the other biomes and convert each into kilograms per square meter per year.
2. Explain the reasons for the differences among biomes. How do these relative differences in the amount of dead plant material in each biome compare to the amount of organic matter in the soil of each biome?

MODULE 12 AP® Review

Preparing for the AP® Exam

In this module, we have learned that terrestrial biomes are categorized by the dominant plant growth forms that exist in a region. These dominant plants coincide with the climates of a region, which we can illustrate graphically using climate diagrams. Based on patterns of climate and plant growth forms, we can categorize nine terrestrial biomes. In the next module, we will see that aquatic biomes can also be categorized, though the criteria are quite different from terrestrial biomes.

AP® Practice Questions

Choose the best answer for the following.

1. In addition to temperature, a terrestrial biome is defined by
   I. annual precipitation.
   II. distinctive animal species.
   III. distinctive plant species.
   (a) I only
   (b) I and II
   (c) I and III
   (d) II and III

2. The precipitation line below the temperature line in a climate diagram shows
   (a) the primary growing season.
   (b) the biome is a desert or tundra.
   (c) when plant growth will be limited by precipitation.
   (d) the seasons in which droughts are most likely to occur.

3. Permafrost is an important factor in which biome?
   I. tundra
   II. boreal forest
   III. cold desert
   (a) I only
   (b) I and II
   (c) II only
   (d) I and III

4. In which biome is plant growth primarily constrained by precipitation?
   (a) boreal forest
   (b) temperate seasonal forest
   (c) temperate grassland
   (d) tropical rainforest

5. Which biome has the highest soil nutrient levels?
   (a) tropical rainforest
   (b) boreal forest
   (c) woodland/shrubland
   (d) temperate seasonal forest

MODULE 13

Aquatic Biomes

Whereas terrestrial biomes are categorized by dominant plant growth forms, aquatic biomes are categorized by physical characteristics such as salinity, depth, and water flow. Temperature is an important factor in determining which species can survive in a particular aquatic habitat, but it is not a factor used to categorize aquatic biomes. Aquatic biomes fall into two broad categories: freshwater and marine. Freshwater biomes include streams, rivers,

Learning Goals

After reading this module you should be able to

- identify the major freshwater biomes.
- identify the major marine biomes.