Acid rain is precipitation in which the pH is below 5.6. The pH of a solution is an expression of relative acidity and alkalinity. It is the negative logarithm of the concentration of the hydrogen ion (H⁺). Many people are surprised to learn that all rainfall is slightly acidic; water reacts with atmospheric carbon dioxide to produce weak carbonic acid. Thus, pure rainfall has a pH of about 5.6, where 1 is highly acidic and 7 is neutral (see Figure 23.16). (Natural rainfall in tropical rain forests has been observed in some instances to have a pH of less than 5.6; this is probably related to acid precursors emitted by the trees.)

Because the pH scale is logarithmic, a pH value of 3 is 10 times more acidic than a pH value of 4 and 100 times more acidic than a pH value of 5. Automobile battery acid has a pH value of 1.

Acid rain includes both wet (rain, snow, fog) and dry (particulate) acidic depositions. The depositions occur near and downwind of areas where the burning of fossil fuels creates major emissions of sulfur dioxide (SO₂) and nitrogen oxides (NOₓ). Although these oxides are the primary contributors to acid rain, other acids are also involved. An example is hydrochloric acid, which is emitted from coal-fired power plants.

Acid rain has likely been a problem at least since the beginning of the Industrial Revolution. In recent decades, however, acid rain has gained more and more attention; and today, it is a major global environmental problem affecting all industrial countries. In the United States, nearly all of the eastern states are affected, as well as West Coast urban centers such as Seattle, San Francisco, and Los Angeles. The problem is also of great concern in Canada, Germany, Scandinavia, and Great Britain. Developing countries that rely heavily on coal, such as China, are facing serious acid rain problems as well.

Causes of Acid Rain
As noted, sulfur dioxide (SO₂) and nitrogen oxides (NOₓ) are the major contributors to acid rain. Amounts of these substances emitted into the environment in the United States are shown in Figures 23.7 and 23.8. Emissions of SO₂ peaked in the 1970s at about 30 million metric tons per year and had declined to about 18 million metric tons per year by 1998. Nitrogen oxides leveled off at about 23 million metric tons per year in the mid-1980s.

In the atmosphere, sulfur dioxide and nitrogen oxides are transformed by reactions with oxygen and water vapor to sulfuric and nitric acids. These acids may travel long distances with prevailing winds to be deposited as acid precipitation (Figure 23.17). As mentioned, such precipitation may take the form of rainfall, snow, or fog. Sulfate and nitrate particles may also be deposited directly on the surface of the land as dry deposition. These
particles may later be activated by moisture to become sulfuric and nitric acids.

Sulfur dioxide is emitted primarily from stationary sources, such as power plants that burn fossil fuels, whereas nitrogen oxides are emitted from both stationary sources and transport-related sources, such as automobiles. Approximately 80% of sulfur dioxide and 65% of nitrogen oxides in the United States come from states east of the Mississippi River.

In some areas, stationary sources have attempted to reduce the local effects of emissions by constructing taller emission stacks. Taller stacks reduced local concentrations of air pollutants but increased regional effects by spreading pollution more widely. Tall stacks increase average residence time of pollutants emitted into the atmosphere from 1–2 days to 10–14 days, because pollutants enter the atmosphere at a greater altitude, where mixing and transport by wind are more effective. Thus, this practice simply created more widespread problems. For example, problems associated with acid precipitation in Canada can be traced to emissions of sulfur dioxide and other pollutants in the Ohio Valley.

Analysis of the distances over which sulfur compounds can be transported before deposition suggests that approximately one-third of the total amount deposited over the eastern United States originates from sources farther away than 500 km (300 mi). Another one-third comes from sources between 200 and 500 km (about 125–300 mi) away, and the remainder comes from sources less than 200 km away.9

**Sensitivity to Acid Rain**

Geology and climatic patterns as well as types of vegetation and soil composition affect the potential impact of acid rain. Figure 23.18, showing areas of the United States and Canada sensitive to acid rain, is based on some of these factors. Sensitive areas are those in which bedrock or soil cannot buffer acid input. Materials (chemicals) that have the ability to neutralize acids are called buffers. Calcium carbonate (CaCO₃), the mineral calcite, which is present in many soils and rock (limestone), is an important natural buffer to acid rain. Hydrogen in acid reacts with calcium carbonate, and the reaction neutralizes acid. Thus, areas less likely to suffer damage from acid rain are those in which bedrock contains limestone or other carbonate material or where soils contain calcium carbonate, which buffers the acid. In contrast, areas with abundant granitic rocks and areas in which soils have little buffering action are sensitive to acid rain. Soils may lose

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**Figure 23.18**

(a) Areas in Canada and the United States that are sensitive to acid rain. (Source: “How Many More Lakes Have to Die?” Canada Today 12, no. 2 [1981]) (b) pH of precipitation over the United States in 2000. Notice the relationship between the numerous sources of SO₂ in the eastern U. S. [in (a)] and low (more acidic) pH values. (Source: National Atmospheric Deposition Program/National Trends Network, 2000.)
their fertility when exposed to acid rain, either because nutrients are leached out by acid water moving through the soil or because the acid in the soil releases elements that are toxic to plants.

**Forest Ecosystems**

It has long been suspected that acid precipitation, whether snow, rain, fog, or dry deposition, adversely affects trees. Studies in Germany led scientists to cite acid rain and other air pollution as the cause of death for thousands of acres of evergreen trees in Bavaria. Similar studies in the Appalachian Mountains of Vermont (where many soils are naturally acidic) suggest that in some locations half the red spruce trees have died in recent years. Damage is attributed in part to acid rain and fog with pH levels of 4.1 and 3.1, respectively.

We have already seen that acid rain can cause loss of nutrients in the soil. This loss of nutrients results in weakening of trees, and they become more susceptible to disease, drought, and consumption by herbivores. As trees weaken and die, there is less habitat and food for birds and animals. Trees stripped of leaves and needles allow more light through to the forest floor, changing the temperature and water content of soil at the surface. This in turn affects what grows on the forest floor and what lives in the soil. Thus, the entire forest ecosystem is affected by acid rain. This is an example of the principle of environmental unity introduced in Chapter 3.

**Lake Ecosystems**

In recent years, fish have disappeared from lakes in Scandinavia. Records from Scandinavian lakes show an increase in acidity accompanied by a decrease in fish (Figure 23.19). The increased acidity has been traced to acid rain, the result of industrial processes in other countries, particularly Germany and Great Britain.

Acid rain affects lake ecosystems in two ways. First, it damages aquatic species (fish, amphibians, and crayfish) directly by disrupting their life processes in ways that limit growth or cause death. For example, crayfish produce fewer eggs in acidic water, and the eggs produced often grow into malformed larvae. Second, acid rain dissolves chemical elements necessary for life in the lake. Once in solution, the necessary elements leave the lake with water outflow. Thus, elements that once cycled in the lake are lost. Without these nutrients, algae do not grow, animals that feed on the algae have little to eat, and animals that feed on these animals also have less food.

To better study the effects of acidification on lakes, scientists in Canada added sulfuric acid to a lake in northwest Ontario over a period of years and observed the

![Figure 23.19](image-url)  
- (a) In Norway, many lakes in the south have severe problems with acid rain.  
- (b) The rain has become more acidic over the last 20 years, as measured at Oslo and at five other sites in southern Norway.  
- (c) The catch of fish, as illustrated by the catch of salmon in the Tovdalselva River of southern Norway, has decreased dramatically.  

effects. When the experiment started, the pH of the lake was 6.8. The following year, owing to addition of the acid, the pH dropped to 6.1. The initial drop in pH was not harmful to the lake; but as more and more acid was added, the pH dropped first to 5.8, then to 5.6, then to 5.4, and finally, five years after the project started, to 5.1. The problems started when the pH was lowered to 5.8. Some species disappeared, and others experienced reproductive failure. At a pH of 5.6, the death rate among lake trout embryos increased. When the pH was lowered to 5.4, lake trout reproduction failed.¹⁰

These experiments have proved valuable in pointing out what we can expect in thousands of other lakes that are now becoming increasingly acidified. The precise processes involved in the toxicity and damage to the lake are poorly understood. However, it is known that acid rain leaches metals, such as aluminum, lead, mercury, and calcium, from the soils and rocks in a drainage basin and discharges them into rivers and lakes. The elevated concentrations of aluminum are particularly damaging to fish, because the metal can clog the gills and cause suffocation. The heavy metals may pose health hazards to humans, because they may become concentrated in fish and then passed on to people, mammals, and birds when the fish are eaten. Drinking water taken from acidic lakes may also have high concentrations of toxic metals.

Not all lakes are as vulnerable to acidification as was the lake in the Ontario experiment. Acid is neutralized in waters with a high carbonate content (in the form of the ion HCO₃⁻). Lakes on limestone or other rocks rich in calcium or magnesium carbonates can therefore readily buffer river and lake water against the addition of acids. Lakes with high concentrations of such elements are called hard-water lakes. Lakes on sand or igneous rocks, such as granite, tend to lack sufficient buffering to neutralize acids and are more susceptible to acidification.¹¹

Thousands of rivers and lakes in the United States and Canada located in areas sensitive to acid rain are currently in various stages of acidification. In Nova Scotia, at least a dozen rivers have water so acidic part of the year that they no longer support healthy populations of Atlantic salmon. In the northeastern United States, about 200 lakes in the Adirondacks are no longer able to support fish, and thousands more are slowly losing the battle with acid rain.

**Human Society**

Acid rain damages not only forests and lakes but also many building materials, including steel, galvanized steel, paint, plastics, cement, masonry, and several types of rock, especially limestone, sandstone, and marble (Figure 23.20). Classical buildings on the Acropolis in Athens and in other cities show considerable decay (chemical weathering) that accelerated in the 20th century as a result of air pollution. The problem has grown to such an extent that buildings require restoration, and statues and other monuments must have protective coatings replaced quite frequently, resulting in costs of billions of dollars a year. Particularly important statues in Greece and other areas have been removed and placed in protective glass containers, with replicas standing in their former outdoor locations for tourists to view.¹²

In the United States, cities along the eastern seaboard are more susceptible to acid rain today because emissions of sulfur dioxide and nitrogen oxide are more abundant there. However, as noted, the problem is moving westward; acid precipitation has been recorded in California. Acid fog in Los Angeles may have a pH as low as 3—over 10 times as acidic as the average acid rain in the eastern United States. In contrast to acid rain, which may form relatively high in the atmosphere and travel long distances, acid fog forms near the ground. Water vapor mixes with pollutants and turns into an acid, which evidently condenses around very fine particles of smog; if the air is sufficiently humid, a fog may form. When the fog eventually dissipates, nearly pure drops of sulfuric acid may be left behind. Tiny particles containing the acid may be inhaled deeply into people's lungs—a considerable health hazard.

Stone decay occurs about twice as rapidly in cities as it does in less urban areas. The damage comes mainly from acid rain and humidity in the atmosphere, as well as from corrosive groundwater.¹² This implies that measuring...

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**Figure 23.20** Damage to a statue in Chicago resulting from an acid deposition (left) and the same statue following restoration (right).
rates of stone decay will tell us something about changes in the acidity of rain and groundwater in different regions and ages. It is now possible, where the ages of stone buildings and other structures are known, to determine if the acid rain problem has changed through time.

Control of Acid Rain
The cause of acid precipitation is known. It is the solution we are struggling with. One solution to lake acidification is rehabilitation by the periodic addition of lime, as has been done in New York state, Sweden, and Ontario. This solution is not satisfactory over a long period, however, because it is expensive and requires a continuing effort. This solution to the acid rain problem is to ensure that the production of acid-forming components in the atmosphere is minimized. The only long-term solution involves decreasing emissions of sulfur dioxide and nitrogen oxides. From an environmental point of view, the best strategy is increasing energy efficiency and conservation measures that result in burning less coal and using nonpolluting alternative energy sources. Another strategy is to utilize pollution abatement technology at power plants to lower emissions of air pollutants. Such technology is expensive and an additional cost in producing energy.

Air pollution also varies with the time of year. For example, smog is usually a problem mostly in the summer months when there is a lot of sunlight; and particulates are a problem in dry months when wildfires are likely and during months when the wind blows across the desert.

Las Vegas: Particulates
Pollution from particulates is a problem in arid regions where little vegetation is present and wind can easily pick up and transport fine dust. For example, the brown haze over Las Vegas, Nevada, is mostly due to naturally occurring particles (PM 10) from the desert environment. Las Vegas in the 1990s was the most rapidly growing urban area in the United States. Population in Clark County, which includes Las Vegas, increased from less than 360,000 in 1970 to nearly 1.5 million in 2000. Las Vegas also has some of the most polluted air in the southwestern United States (Figure 23.21). As mentioned, the main problem is the nearly 80,000 metric tons of PM 10 particles that enter the air in the Las Vegas region. About 60% of the dust comes from new construction sites, dirt roads, and vacant land. The remainder is natural wind-blown dust. Las Vegas also has a carbon monoxide pollution problem from vehicles, but it is the particulates that are causing concern, possibly leading to future Environmental Protection Agency sanctions and growth restrictions.

Haze from Afar
Air quality concerns are not restricted to urban areas. For example, the North Slope of Alaska is a vast strip of land approximately 200 km (125 mi) wide that is considered by many to be one of the last unspoiled wilderness areas left on Earth. It seems logical to assume that air in the Arctic environments of Alaska would be pristine in quality, except perhaps near areas where petroleum is being vigorously developed. However, ongoing studies suggest that the North Slope has an air pollution problem that originates from sources in Eastern Europe and Eurasia.

It is suspected that pollutants from the burning of fossil fuels in Eurasia are transported via the jet stream, moving at speeds that may exceed 400 km/hr (250 mi/hr), northeast from Eurasia over the North Pole and eventually to the North Slope of Alaska. There, the air mass slows, stagnates, and produces what is known as the Arctic haze. Concentrations of air pollutants, which include oxides of sulfur and nitrogen, are high enough that the air quality is being compared with that of some eastern U.S. cities, such as Boston. Air quality problems in remote areas such as Alaska have significance as we try to understand air pollution at the global level.

Another global event occurred in the spring of 2001, when a white haze consisting of dust from Mongolia and industrial particulate pollutants arrived in North America.