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ENVIRONMENTAL ESSENTIALS

THIRD EDITION

THE
SCIENCE
BEHIND
THE
STORIES

JAY WITHGOTT
SCOTT BRENNAN

JAY WITHGOTT • SCOTT BRENNAN

ESSENTIAL ENVIRONMENT

THE SCIENCE BEHIND THE STORIES

Third Edition

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the Great Plains and the Southeast, where cold air from Canada and warm air from the Gulf of Mexico frequently meet.

Understanding how the atmosphere functions can help us predict violent storms and warn people of their approach. Such knowledge also can help us comprehend how our pollution of the atmosphere affects climate, ecological systems, economies, and human health.

Outdoor Air Pollution

Throughout human history, we have made the atmosphere a dumping ground for our airborne wastes. Whether from primitive wood fires or modern coal-burning power plants, people have generated significant quantities of **air pollutants**, gases and particulate material added to the atmosphere that can affect climate or harm people or other organisms. **Air pollution** refers to the release of air pollutants.

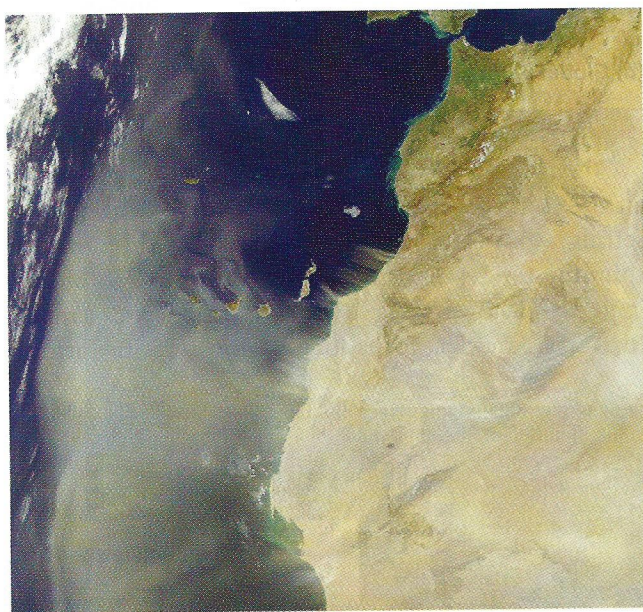
In recent decades, government policy and improved technologies have helped us diminish most types of *outdoor air pollution* (often called *ambient air pollution*) in industrialized nations. However, outdoor air pollution remains a problem, particularly in developing nations and in urban areas. Moreover, arguably the

greatest air pollution problem today is our emission of greenhouse gases that contribute to global climate change. We discuss this issue separately and in depth in Chapter 14.

Natural sources can pollute

When we think of outdoor air pollution, we tend to envision smokestacks belching black smoke from industrial plants. However, natural processes produce a great deal of the world's air pollution (**Figure 13.5**). Winds sweeping over arid terrain can send huge amounts of dust aloft—sometimes across oceans from one continent to another. Volcanic eruptions (• pp. 240–242) release large quantities of particulate matter and sulfur dioxide into the troposphere, and major eruptions may blow matter into the stratosphere. Fires (• p. 203) in forests and grasslands also generate soot and gases, and over 60 million ha (150 million acres) of forest and grassland burn in a typical year.

Human activities and land use policies can worsen some of these natural impacts. For instance, farming and grazing practices that strip vegetation from the soil allow wind erosion and promote dust storms (• pp. 138–139, 143, 243). And many fires in the tropics are set by people clearing and burning forest to make way for agriculture.



(a) Dust storm blowing from Africa over the Atlantic



(b) Mount Saint Helens erupting, 1980

FIGURE 13.5 Massive dust storms are one type of natural air pollution. Storms blowing across the Atlantic Ocean from Africa to the Americas (a) carry fungal and bacterial spores linked to die-offs in Caribbean coral reef systems. Strong westerlies have lifted soil from deserts in Mongolia and China and carried it thousands of miles across the Pacific Ocean to North America. Volcanoes are another source of natural air pollution. The eruption of Mount Saint Helens (b) in Washington State in 1980 produced 1.1 billion m³ (1.4 billion yd³) of ash that circled the planet.

We create outdoor air pollution

Human activity also introduces new sources of air pollution. As with water pollution, air pollution can emanate from *point sources* or *non-point sources* (• p. 266). A point source describes a specific spot—such as a factory's smokestacks—where large quantities of pollutants are discharged. In contrast, non-point sources are more diffuse, consisting of many small sources (such as millions of automobiles).

Primary pollutants, such as soot and carbon monoxide, are pollutants emitted into the troposphere in a form that can be directly harmful or that can react to form harmful substances. Harmful substances produced when primary pollutants interact or react with constituents of the atmosphere are called **secondary pollutants**.

Clean Air Act legislation addresses pollution in the United States

To address air pollution in the United States, Congress has passed a series of laws, including the **Clean Air Act**, first enacted in 1963 and amended multiple times since, particularly in 1970 and 1990. This body of legislation funds research into pollution control, sets standards for air quality, imposes limits on emissions from new stationary and mobile sources, and enables citizens to sue parties that violate the standards. It also introduced an emissions trading program (• p. 45) for sulfur dioxide. Beginning in 1995, businesses and utilities were allocated permits for emitting this pollutant and could buy, sell, or trade these allowances with one another. Each year the overall amount of allowed pollution was decreased. This successful market-based incentive program has spawned similar programs at state and regional levels and for other pollutants.

Under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) sets nationwide standards for emissions of pollutants and for concentrations of pollutants in ambient air. However, it is largely up to the states to monitor air quality and to develop, implement, and enforce regulations within their boundaries. States submit implementation plans to the EPA for approval, and if a state's plans are not adequate, the EPA may take over enforcement in that state.

The EPA sets standards for "criteria pollutants"

The EPA and the states focus on six criteria pollutants, pollutants judged to pose especially great threats to human health—carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), tropospheric ozone (O₃),

particulate matter, and lead (Pb). For these, the EPA has established maximum concentrations allowable in ambient outdoor air.

Carbon monoxide *Carbon monoxide* is a colorless, odorless gas produced primarily by the incomplete combustion of fuel. Vehicles and engines account for 78% of these emissions in the United States; other sources include industrial processes, combustion of waste, and residential wood burning. Carbon monoxide can bind irreversibly to hemoglobin in our red blood cells, preventing the hemoglobin from binding with oxygen.

Sulfur dioxide Like CO, *sulfur dioxide* is a colorless gas, but unlike CO, it has a pungent odor. Most SO₂ pollution results from the combustion of coal for electricity generation and industry. During combustion, elemental sulfur (S) in coal reacts with oxygen gas (O₂) to form SO₂. Once in the atmosphere, SO₂ may react to form sulfur trioxide (SO₃) and sulfuric acid (H₂SO₄), which may return to Earth in acidic deposition (• pp. 295–297).

Nitrogen dioxide *Nitrogen dioxide* is a foul-smelling, reddish brown gas that contributes to smog and acidic deposition. Along with nitric oxide (NO), NO₂ belongs to a family of compounds called *nitrogen oxides* (NO_x). Nitrogen oxides result when atmospheric nitrogen and oxygen react at the high temperatures created by combustion engines. Over half of U.S. NO_x emissions result from combustion in vehicle engines. Electrical utility and industrial combustion account for most of the rest.

Tropospheric ozone Although ozone in the stratosphere protects us from UV radiation, O₃ from human activity accumulates low in the troposphere. Here, this colorless gas is a secondary pollutant, created by the interaction of sunlight, heat, nitrogen oxides, and volatile carbon-containing chemicals. A major component of smog, O₃ poses health risks as a result of its instability as a molecule; this triplet of oxygen atoms will readily release one of its threesome, leaving a molecule of oxygen gas and a free oxygen atom. The oxygen atom (a free radical) may then participate in reactions that can injure living tissues and cause respiratory problems. *Tropospheric ozone* is the pollutant that most frequently exceeds the EPA standard.

Particulate matter *Particulate matter* is composed of solid or liquid particles small enough to be suspended in the atmosphere and able to damage respiratory tissues when inhaled. Particulate matter includes primary pollutants such as dust and soot as well as secondary pollutants such as sulfates and nitrates. Most particulate matter is wind-blown dust; human activity accounts

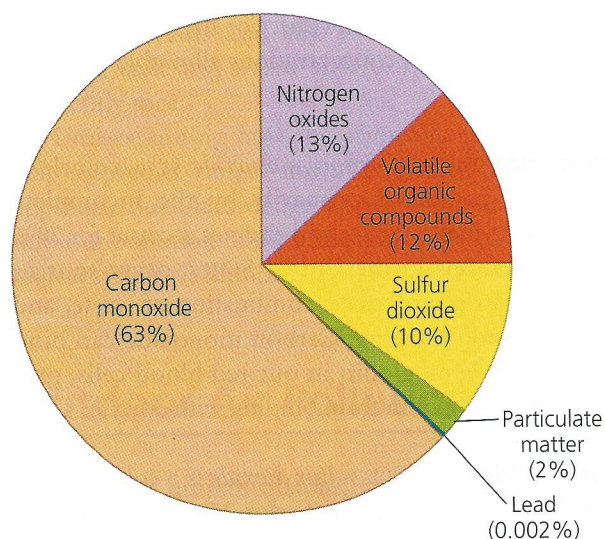


FIGURE 13.6 In 2007, the United States emitted 129 million tons of the six major pollutants whose emissions are monitored by the EPA and state and local agencies. Carbon monoxide accounted for most of these emissions, by mass. Data from U.S. EPA, 2008.

for much of the rest. Along with sulfur dioxide, it was largely the emission of particulate matter from industrial and residential coal combustion that produced London's 1952 killer smog and the deaths resulting from that episode.

Lead Lead is a heavy metal that enters the atmosphere as a particulate pollutant. The lead-containing compounds tetraethyl lead and tetramethyl lead, when added to gasoline, improve engine performance. However, exhaust from leaded gasoline emits lead into the atmosphere, from which it can be inhaled or can be deposited on land and water. Lead can enter the food chain, accumulate within body tissues, and cause central nervous system malfunction and many other ailments. Since the 1980s, leaded gasoline has been phased out in many industrialized nations (• p. 7), and lead pollution has plummeted. However, many developing nations still add lead to gasoline and experience significant lead pollution.

Agencies monitor emissions

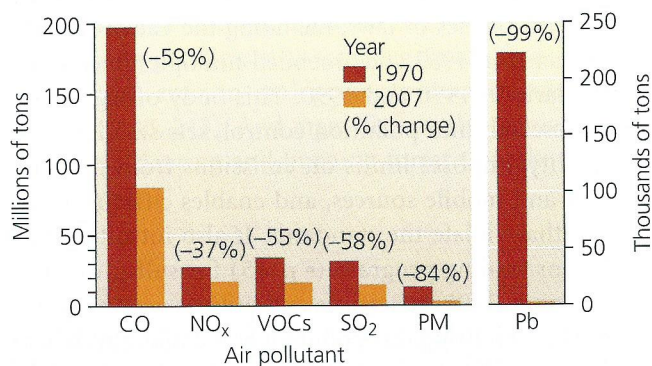
Besides measuring concentrations of the six criteria pollutants in ambient air, state and local agencies also monitor, calculate, and report to the EPA emissions of pollutants that affect ambient concentrations of the six criteria pollutants. These include the four criteria pollutants that are primary pollutants (carbon monoxide, sulfur dioxide, particulate matter, and lead), as well as all nitrogen oxides (because NO reacts to form NO_2 , which is both a primary and secondary pollutant). Tropospheric ozone is a secondary pollutant only, so there are no emissions to monitor.

Instead we monitor emissions of *volatile organic compounds (VOCs)*, carbon-containing chemicals (such as hydrocarbons; • p. 56) that can react to produce ozone and other secondary pollutants. The largest sources of anthropogenic VOC emissions include industrial use of solvents and vehicle emissions.

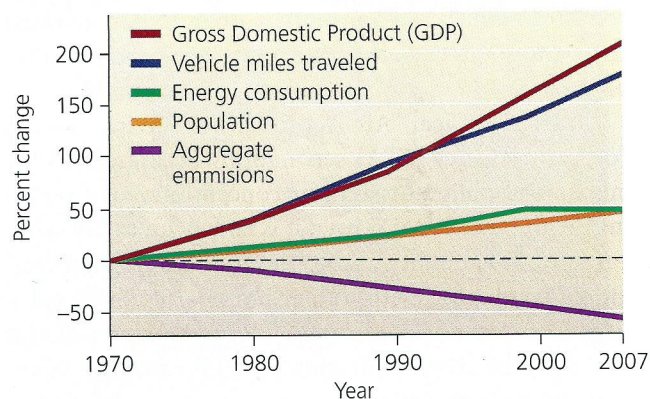
In the United States in 2007, human activity polluted the air with 129 million tons of the six monitored pollutants. Carbon monoxide was the most abundant pollutant by mass, followed by NO_x , VOCs, and SO_2 (Figure 13.6).

We have reduced air pollution

Since the Clean Air Act of 1970, we have reduced emissions of each of these six monitored pollutants, and total emissions of the six together have declined by 57% (Figure 13.7a). This decrease has occurred despite substantial increases in the nation's population, energy consumption, miles traveled by vehicle, and gross domestic product (Figure 13.7b).



(a) Declines in emissions of six major pollutants



(b) Trends in major indicators

FIGURE 13.7 Shown in (a) are data for the six major ambient air pollutants whose emissions the EPA monitors. Emissions of each of these pollutants have declined substantially in the United States since 1970, and emissions from all six together have declined by 57%. This decrease in emissions has occurred despite increases (b) in U.S. population, energy consumption, vehicle miles traveled, and gross domestic product. Go to [GRAPHIT!](http://www.myenvironmentplace.com) at www.myenvironmentplace.com. Data from U.S. EPA, 2008.

There are several reasons for these declines. Cleaner-burning motor vehicle engines and automotive technologies such as catalytic converters have played a large part, decreasing the emissions of carbon monoxide and several other pollutants. The sulfur dioxide permit trading program (• pp. 44–45) and clean coal technologies (• p. 339) have reduced SO_2 emissions. Technologies such as baghouse filters, electrostatic precipitators, and **scrubbers** (Figure 13.8) that chemically convert or physically remove airborne pollutants before they are emitted from smokestacks have allowed factories, power plants, and refineries to decrease emissions of several pollutants. And the phaseout of leaded gasoline caused U.S. lead emissions to plummet by 93% from 1980 to 1990 alone. The United States still has a long way to go in controlling outdoor air pollution, but the progress since 1970 represents a substantial accomplishment in safeguarding human health and environmental quality.

Other industrialized nations are also reducing emissions and improving air quality, thanks to improved technologies and targeted federal policies. England is among them. Between 1996 and 2005, London achieved a

56% reduction in CO emissions, a 41% drop in NO_x emissions, a 28% decline in particulate matter release, and a 73% decrease in SO_2 emissions. Only tropospheric ozone showed an increase, rising 33%. With the congestion-charging program and related transportation initiatives, Mayor Livingstone hoped to turn around the trend in ozone pollution as well. However, after the program's first few years, experts determined that most emissions reductions in London were due not to the congestion-charging program, but to improvements in automotive technology mandated by the European Union.

We are also reducing **toxic air pollutants**, chemicals known to cause serious health or environmental problems. These include substances known to cause cancer, reproductive defects, or neurological, developmental, immune system, or respiratory problems. The 1990 Clean Air Act identifies 188 toxic air pollutants, ranging from the heavy metal mercury (from coal-burning power plant emissions and other sources) to VOCs such as benzene (a component of gasoline). The EPA estimates that because of Clean Air Act regulations, from 1990 to 2002 emissions of toxic air pollutants decreased by 35%.

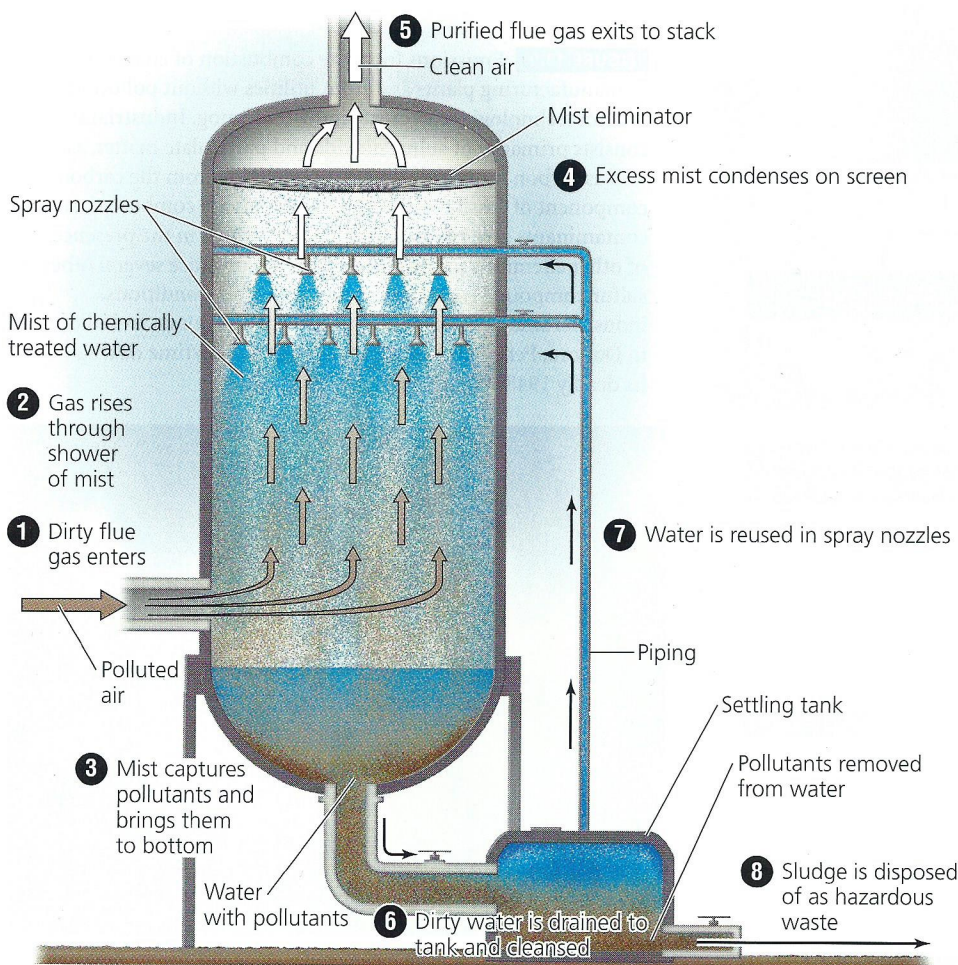
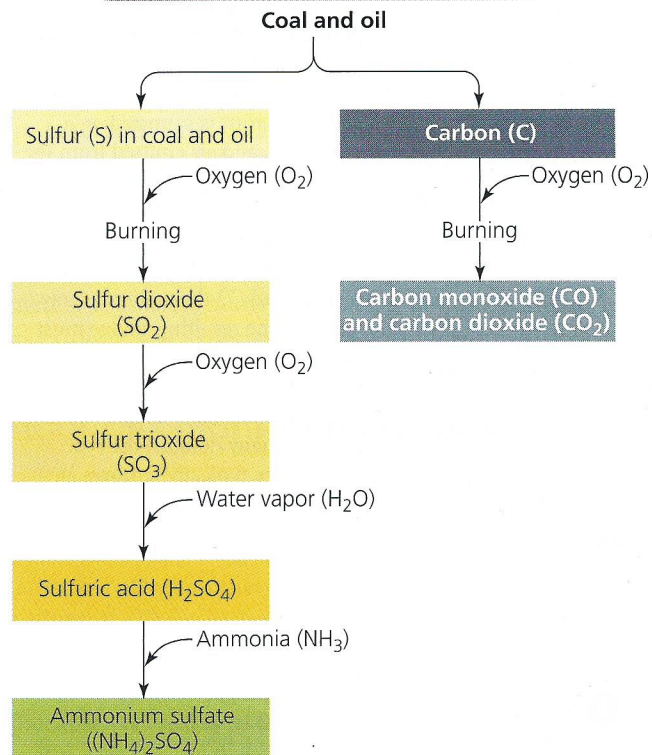
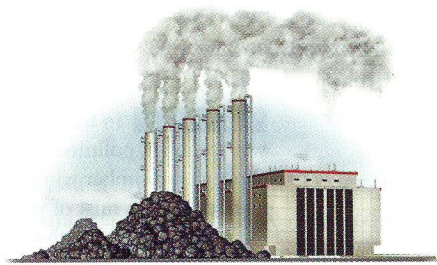


FIGURE 13.8 In this spray-tower wet scrubber, polluted air (1) rises through a chamber while arrays of nozzles spray a mist of water mixed with lime or other active chemicals (2). The falling mist captures pollutants and carries them to the bottom of the chamber (3), essentially washing them out of the air. Excess mist is captured on a screen (4), and air emitted from the scrubber has largely been cleansed (5). Periodically, the dirty water is drained from the chamber (6), cleansed in a settling tank, and recirculated (7) through the spray nozzles. The resulting sludge must be disposed of (8) as hazardous waste (• pp. 389–393). Scrubbers and other pollution-control devices come in many designs; the type shown here typically removes at least 90% of particulate matter and gases such as sulfur dioxide.

Recent policy has been contentious

Despite the gains in air quality made under the Clean Air Act, the George W. Bush administration vigorously pushed proposals to overturn key aspects of the legislation. The EPA under Bush proposed to abolish *new source review*, which required aging plants to install the “best available” current technology for pollution control when they upgrade their plants. In 2006, federal courts struck down the EPA’s attempts to eliminate new source review. Then, with its *Clear Skies* initiative, the Bush administration aimed to abandon a command-and-control policy approach and establish a market-based cap-and-trade program for sulfur dioxide, nitrogen oxides, and mercury. In 2005, members of the U.S. Senate halted the Clear Skies legislation, concluding that it would *increase* pollution. An independent Congressional Research Service analysis judged that the EPA had skewed its analysis of costs and benefits to promote the legislation.



(a) Burning sulfur-rich oil or coal without adequate pollution control technologies

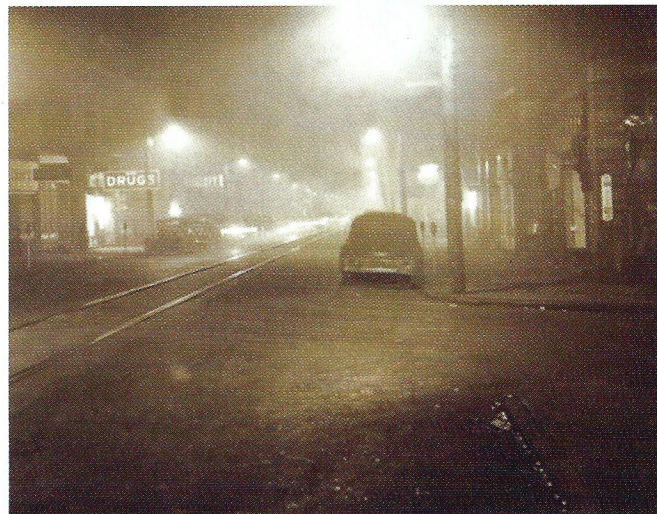
Burning fossil fuels produces industrial smog

In response to an increasing incidence of fogs polluted by the smoke of Britain’s industrial revolution, an early British scientist coined the term *smog*. Today the term is used worldwide to describe unhealthy mixtures of air pollutants that often form over urban areas.

The “killer smog” that enveloped London in 1952 was what we now call **industrial smog**, or gray-air smog. When coal or oil is burned, some portion is completely combusted, forming CO_2 ; some is partially combusted, producing CO ; and some remains unburned and is released as soot, or particles of carbon. Moreover, coal may contain contaminants including mercury and sulfur. Sulfur reacts with oxygen to form sulfur dioxide, which can undergo a series of reactions to form sulfuric acid and ammonium sulfate (Figure 13.9a). These chemicals and others produced by further reactions, along with soot, are the main components of industrial smog and produce its characteristic gray color.

Industrial smog is less common today in developed nations than it was 50–100 years ago. In the wake of the 1952 London episode and others, governments of most

FIGURE 13.9 Emissions from the combustion of coal and oil in manufacturing plants and from utilities without pollution-control technologies can create industrial smog. Industrial smog consists primarily of sulfur dioxide and particulate matter, as well as carbon monoxide and carbon dioxide from the carbon component of fossil fuels. When fossil fuels are combusted, sulfur contaminants give rise to sulfur dioxide, which in the presence of other chemicals in the atmosphere can produce several other sulfur compounds (a). Under certain weather conditions, industrial smog can blanket whole towns or regions, as it did in Donora, Pennsylvania, shown here in the daytime during its deadly 1948 smog event (b).



(b) Donora, Pennsylvania, at midday in the 1948 smog event

developed nations began regulating industrial emissions. However, in industrializing regions such as China, India, and Eastern Europe, coal burning (by industry and by citizens heating and cooking in their homes), combined with lax air pollution controls, produces industrial smog that poses significant health risks in many areas.

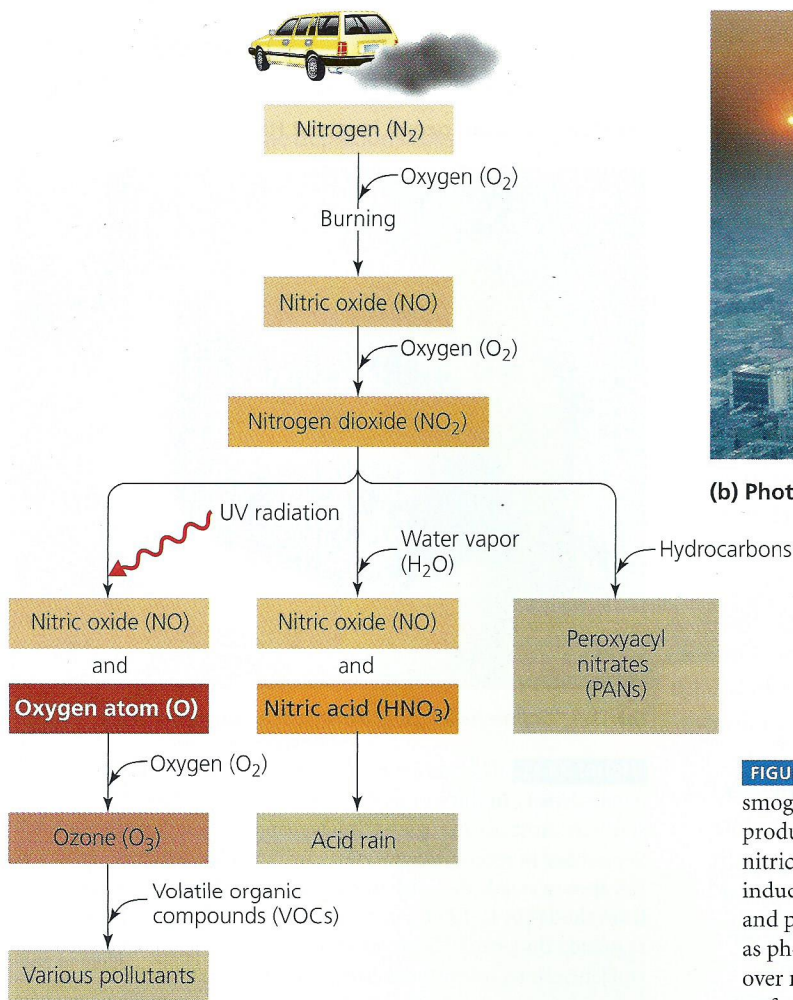
Weather plays a role in smog formation, as it did in London in 1952. A similar event occurred 4 years earlier in Donora, Pennsylvania. Here, air near the ground cooled during the night, and because Donora is located in hilly terrain, too little morning sun reached the valley floor to warm and disperse the cold air. The resulting thermal inversion trapped smog containing particulate matter emissions from a steel and wire factory. Twenty-one people were killed, and over 6,000 people—nearly half the town—became ill (Figure 13.9b).

Hilly topography facilitates smog in many other cities where surrounding mountains trap air and create inversions—including the Los Angeles basin. Modern-day L.A., however, suffers from a different type of smog, one called photochemical smog.

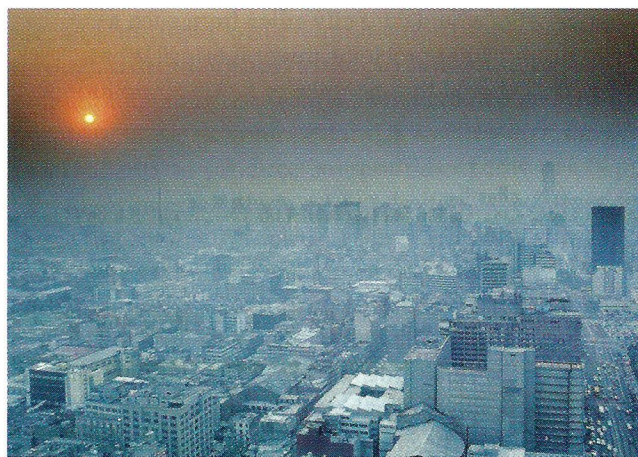
Photochemical smog is produced by a series of reactions

Photochemical smog, or brown-air smog, is formed by light-driven chemical reactions of primary pollutants and normal atmospheric compounds that produce a mix of over 100 different chemicals, tropospheric ozone often being the most abundant among them (Figure 13.10a). High levels of NO_2 cause photochemical smog to form a brownish haze (Figure 13.10b). Hot, sunny, windless days in urban areas provide perfect conditions for the formation of photochemical smog. Exhaust from morning traffic releases large amounts of NO and VOCs. Sunlight then promotes the production of ozone and other constituents of photochemical smog. Levels of photochemical pollutants in urban areas typically peak in midafternoon and, at sufficient levels, can irritate people's eyes, noses, and throats.

Photochemical smog afflicts many major cities, especially those with topography and weather conditions that promote it. London's congestion-charging program



(a) Formation of photochemical smog



(b) Photochemical smog over Mexico City

FIGURE 13.10 Nitric oxide, a key element of photochemical smog, can start a chemical chain reaction (a) that results in the production of other compounds, including nitrogen dioxide, nitric acid, ozone, and peroxyacyl nitrates (PANs). PANs can induce further reactions that damage living tissues in animals and plants. Nitric acid contributes to acidic deposition as well as photochemical smog. Photochemical smog is common today over many urban areas, especially those with hilly topography or frequent inversion layers. Mexico City (b) is one city that frequently experiences photochemical smog.

should in theory cut down on photochemical smog by reducing traffic exhaust. However, a reduction has been hard to prove so far. During the program's first year, unusual weather resulted in optimal conditions for photochemical reactions, and smog intensified. In 2006, street repairs caused congestion to increase, despite lower numbers of cars. And throughout the period, pollution from surrounding areas has continued to contribute to smog in the central city.

Some U.S. states have cut emissions leading to photochemical smog, through vehicle inspection programs. Drivers in 34 states are required to have their vehicle exhaust inspected periodically at check stations to maintain their registrations. Although a failed "smog check" means inconvenience for the auto owner, these programs help maintain vehicle condition and make the air measurably cleaner for all of us.

Weighing THE Issues

Congestion Charging

Does the city you live in, or your nearest major city, suffer from air pollution? Do you think this city should adopt a congestion-charging program like London's? What benefits would your city enjoy from such a program, and what problems might it bring? What other steps should this city take to tackle air pollution?

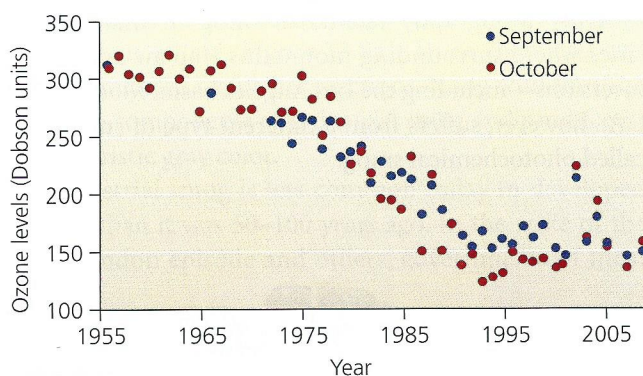
Synthetic chemicals deplete stratospheric ozone

Although ozone in the troposphere is a pollutant that contributes to photochemical smog, ozone in the stratosphere absorbs incoming ultraviolet radiation from the sun, shielding life on Earth's surface. In the 1960s, atmospheric scientists began wondering why their measurements of stratospheric ozone were lower than theoretical models predicted. Researchers hypothesizing that chemicals must be depleting ozone finally pinpointed a group of human-made compounds derived from simple hydrocarbons, such as ethane and methane, in which hydrogen atoms are replaced by chlorine, bromine, or fluorine. One class of such compounds, **chlorofluorocarbons (CFCs)**, was being mass-produced by industry at a rate of a million metric tons per year.

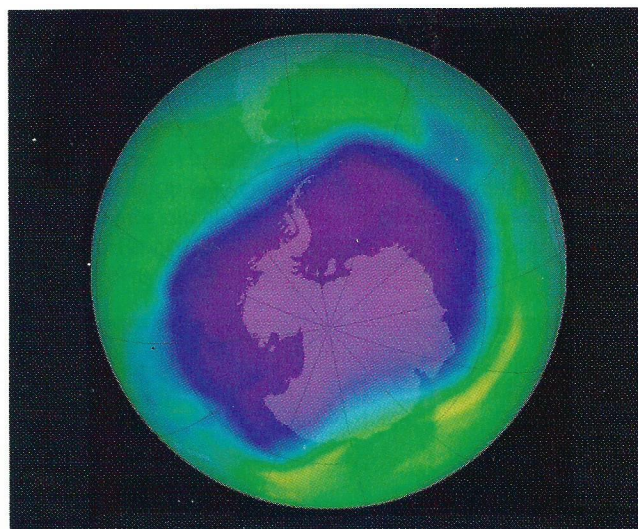
In 1974, atmospheric scientists Sherwood Rowland and Mario Molina showed that CFCs could deplete stratospheric ozone by releasing chlorine atoms that split ozone molecules, creating from each of them an O_2 molecule and a ClO molecule. Three years earlier, researcher James McDonald had predicted that ozone loss, by allowing more UV radiation to reach the surface, would cause thousands more skin cancer cases each year. Then

in 1985, scientists from the British Antarctic Survey announced that stratospheric ozone levels over Antarctica each autumn had declined by 40–60% in the previous decade, leaving a thinned ozone concentration that was soon dubbed the *ozone hole* (Figure 13.11).

Research over the next few years confirmed the link between CFCs and ozone loss in the Antarctic. It also indicated that depletion was occurring in the Arctic, and perhaps globally. Already concerned about skin cancer, scientists were becoming anxious over other possible effects of increased UV radiation, including harm to crops and to ocean phytoplankton, the base of the marine food chain.



(a) Monthly mean ozone levels at Halley, Antarctica



(b) The "ozone hole" over Antarctica, September 24, 2006

FIGURE 13.11 The "ozone hole" consists of a region of thinned ozone density in the stratosphere over Antarctica and the southernmost ocean regions. It has reappeared seasonally each September in recent decades. Data from Halley, Antarctica (a), show a steady decrease in stratospheric ozone concentrations from the 1960s to 1990. Ozone-depleting CFCs began to be regulated under the Montreal Protocol in 1987, and ozone concentrations stopped declining. Colorized satellite imagery from September 24, 2006 (b), shows the "ozone hole" (blue) at its maximal recorded extent to date. Data from British Antarctic Survey.

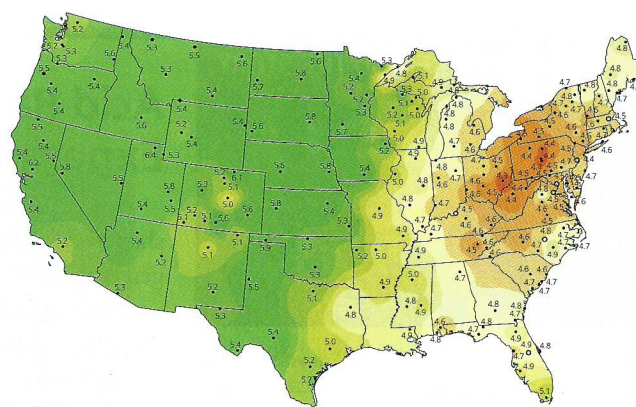
The Montreal Protocol addressed ozone depletion

International efforts to restrict CFC production finally bore fruit in 1987 with the Montreal Protocol. In this treaty, signatory nations (eventually numbering 180) agreed to cut CFC production in half. Five follow-up agreements deepened the cuts, advanced timetables for compliance, and addressed additional ozone-depleting chemicals. Today the production and use of ozone-depleting compounds has fallen by 95% since the late 1980s, and scientists can discern the beginnings of long-term recovery of the ozone layer (although many of the CFCs emitted into the troposphere have yet to diffuse up into the stratosphere, and CFCs are slow to dissipate or break down). Industry was able to shift to alternative, environmentally safer chemicals, which have largely turned out to be cheaper and more efficient.

Because of its success in addressing ozone depletion, the Montreal Protocol is widely seen as a model for international cooperation on other pressing global problems, such as persistent organic pollutants (• pp. 229–230), climate change (• pp. 322–323), and biodiversity loss (• p. 180).

Acidic deposition is another transboundary pollution issue

Just as stratospheric ozone depletion crosses political boundaries, so does **acidic deposition**, the deposition of acidic or acid-forming pollutants from the atmosphere onto Earth's surface. Acidic deposition can take place by precipitation (commonly referred to as *acid rain*, but also including acid snow, sleet, and hail), by fog, by gases, or by the deposition of dry particles. Acidic deposition is one type of **atmospheric deposition**, which refers more broadly to the wet or dry deposition on land of a wide variety of pollutants, including mercury, nitrates, organochlorines, and others.



Lab pH

≥ 5.3	4.9 – 5.0	4.5 – 4.6
5.2 – 5.3	4.8 – 4.9	4.4 – 4.5
5.1 – 5.2	4.7 – 4.8	4.3 – 4.4
5.0 – 5.1	4.6 – 4.7	< 4.3

FIGURE 13.13 This U.S. map shows pH values for precipitation. Precipitation is most acidic in the Northeast and Midwest, generally near and downwind from (roughly east of) areas of heavy industry. Data are for 2006, from the National Atmospheric Deposition Program.

Acidic deposition originates primarily with sulfur dioxide and nitrogen oxides, pollutants produced largely through fossil fuel combustion by automobiles, electric utilities, and industrial facilities. Once emitted into the troposphere, these pollutants can react with water, oxygen, and oxidants to produce compounds of low pH (• pp. 55–56), primarily sulfuric acid and nitric acid. Suspended in the troposphere, droplets of these acids may travel days or weeks for hundreds of kilometers (**Figure 13.12**).

Because the pollutants leading to acid deposition can travel long distances, their effects may be felt far from their sources—a situation that has led to political bickering among the leaders of states and nations (**Figure 13.13**).

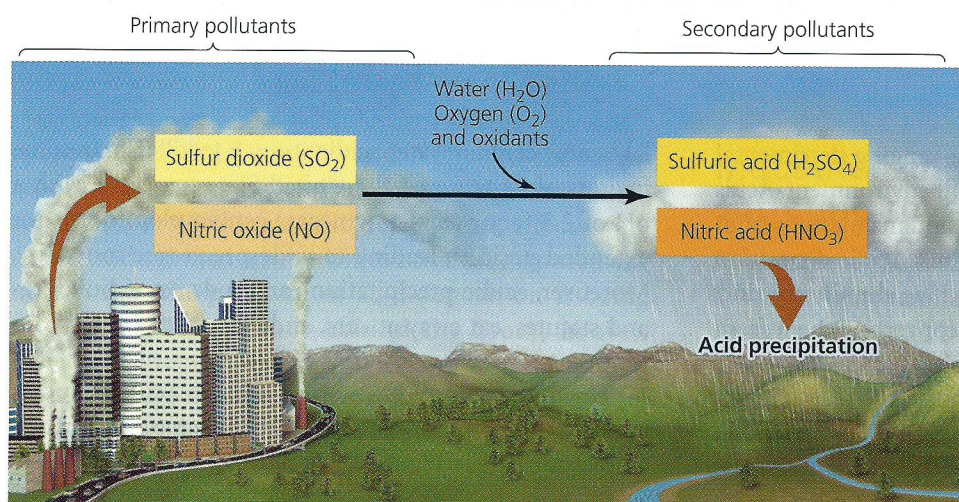
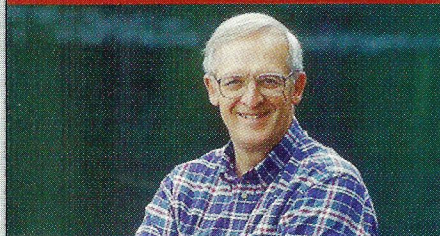


FIGURE 13.12 Acidic deposition can have consequences far downwind from its source. Sulfur dioxide and nitric oxide emitted by industries and utilities create sulfuric acid and nitric acid through chemical reactions in the atmosphere. These acidic compounds descend to Earth's surface in rain, snow, fog, and dry deposition.

THE SCIENCE BEHIND THE STORY



Dr. Gene E. Likens, *Institute of Ecosystem Studies*

Acidic deposition involves subtle and incremental changes in pH levels that take place over long periods of time, so no single experiment can give us a complete picture of acidic deposition's effects. Nonetheless, one long-term study conducted in New Hampshire's White Mountains has been vital to our understanding of acidic deposition in the United States.

Established by the U.S. Forest Service in 1955, Hubbard Brook Experimental Forest was initially devoted to research on hydrology, the study of water flow through forests and streams. In 1963, in collaboration with scientists at Dartmouth University, Hubbard Brook researchers broadened their focus to include a long-term study of nutrient cycling in forest ecosystems. Since then, they have collected and analyzed weekly samples of precipitation. The measurements make up the longest-running North American record of acid precipitation and have helped

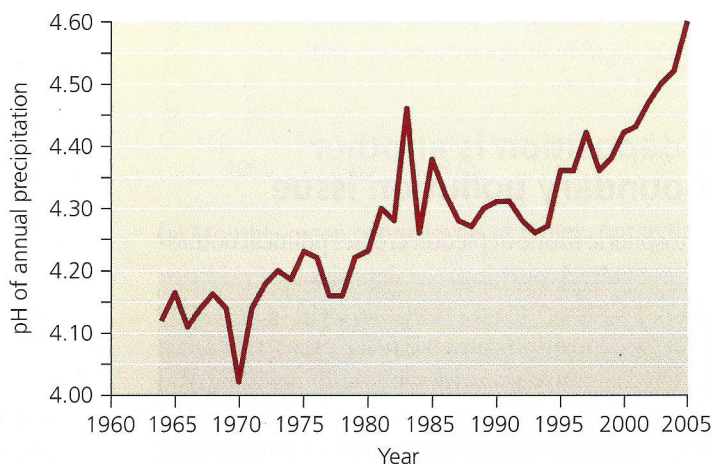
Acid Rain at Hubbard Brook Experimental Forest

shape U.S. policy on sulfur and nitrogen emissions.

Throughout Hubbard Brook's 3,160 ha (7,800 acres), small plastic collecting funnels channel precipitation into clean bottles, which researchers retrieve and replace each week. Hubbard Brook's laboratory measures acidity and conductivity, which indicates the amount of salts and other electrolytic contaminants dissolved in the water. Concentrations of sulfuric acid, nitrates, ammonia, and other compounds are measured elsewhere.

By the late 1960s, ecologists Gene Likens, F. Herbert Bormann, and others had found that precipitation at Hubbard Brook was several hundred times more acidic than natural rainwater. By the early 1970s, other studies indicated that precipitation from Pennsylvania to Maine had pH values averaging around 4 and that individual rainstorms showed values as low as 2.1—almost 10,000 times more acidic than ordinary rainwater.

In 1978, the National Atmospheric Deposition Program



Since the Clean Air Act legislation in 1970 and 1990, precipitation at the Hubbard Brook Experimental Forest has become slightly less acidic. However, it is still far more acidic than is natural precipitation. Data from Likens, G. E. 2004. *Ecology* 85: 2355–2362.

Acidic deposition can have wide-ranging detrimental effects on ecosystems and on our built environment. Acids leach basic minerals such as calcium and magnesium from soil, harming plants and soil organisms. Acidic deposition also “mobilizes” toxic metal ions such as aluminum, zinc, mercury, and copper by chemically converting them from insoluble forms to soluble forms. Elevated aluminum in the soil hinders water and nutrient uptake by plants, and it may damage crops. Runoff may significantly acidify streams, rivers, and lakes—and thousands of northern

lakes now contain water acidic enough to kill fish. In some regions of Britain and the United States, acid fog with a pH of 2.3 (equivalent to vinegar) can envelop forests for extended periods, leading to widespread tree mortality. Moreover, acidic precipitation can erode stone buildings and statues, eat away at cars, and erase the writing from tombstones.

New technology has helped reduce acidic deposition; for example, scrubbers that filter pollutants in smokestacks (see Figure 13.8) have allowed factories to



Acidic deposition killed these trees on Mount Mitchell in North Carolina.

was launched to monitor precipitation and dry deposition across the United States. Initially consisting of 22 sites, including Hubbard Brook, the program now consists of more than 200, each of which gathers weekly data on acidic deposition and deposition of other substances. By the late 1980s, this program had produced a nationwide map of pH values (see Figure 13.13). The most severe problems were found to be in the Northeast, where prevailing winds blow emissions from coal-fired power plants in the Midwest. Scientists hypothesized that when sulfur dioxide,

nitrogen oxides, and other pollutants arrived in the Northeast, they were absorbed by water droplets in clouds, converted to acidic compounds such as sulfuric acid, and deposited on farms, forests, and cities in rain or snow.

The Clean Air Act of 1970 helped reduce acidic deposition in the Northeast. At an area of Hubbard Brook known as Watershed 6, average pH has increased steadily since then (see the first figure). In 1990, as a consequence of the Hubbard Brook study and the nationwide research that followed, the Clean Air Act was amended to further restrict emissions

of sulfur dioxide and other acid-forming compounds.

Nonetheless, acidic deposition continues to be a problem, and some long-term consequences are now becoming clear. In 1996, researchers reported that about half of the calcium and magnesium in Hubbard Brook's soils had leached out. Meanwhile, acidic deposition had increased the concentration of aluminum in the soil, which can prevent tree roots from absorbing nutrients. The resulting nutrient deficiency slows forest growth and weakens trees, making them more vulnerable to drought and insects (see the second figure). It also reduces the ability of soil and water to neutralize acidity, making the ecosystem increasingly vulnerable to further acidic inputs.

In October 1999, researchers used a helicopter to distribute 50 tons of a calcium-containing mineral called wollastonite over one of Hubbard Brook's watersheds. Their objective was to raise the concentration of base cations to estimated historical levels. Over the next 50 years, scientists plan to evaluate the impact of calcium addition on the watershed's soil, water, and life. By providing a comparison to watersheds in which calcium remains depleted, the results should provide new insights into the consequences of acid rain and the possibilities for reversing its negative effects.

decrease emissions of SO_2 and NO_x . Still, a recent report by scientists at New Hampshire's Hubbard Brook research forest, where acidic deposition's effects were first demonstrated in the United States, disputed the notion that the problem of acid deposition is being solved (see **The Science behind the Story**, above). Instead, the report said, the effects are worse than first predicted, and the mandates of the 1990 Clean Air Act are not adequate to restore ecosystems in the northeastern United States.

Industrializing nations are suffering severe air pollution

The data on acid deposition show that despite our advances in controlling outdoor air pollution in North America, more can be done. And more can certainly be done in the world's developing nations, where air pollution is growing worse. In nations that are industrializing today, rapidly proliferating factories and power plants are releasing emissions with little effort to control pollution,

while citizens continue to burn traditional sources of fuel such as wood and charcoal for cooking and home heating.

China suffers among the world's worst air pollution. Four out of five Chinese cities surveyed by the World Bank in 2000 suffered SO_2 or NO_2 emissions above the threshold set by the World Health Organization. Together, China and India suffer 58% of the 1.8 million premature deaths that the World Bank estimates occur each year globally as a result of outdoor air pollution. Indeed, as Beijing prepared for the 2008 Olympics, controlling air pollution was one of its greatest challenges. In the months before the Games, long-distance runners and other athletes threatened to withdraw from events because they feared harm to their health from breathing the air in the Chinese capital. China responded by temporarily shutting down industries in the region in an attempt to clear the air.

Industrializing nations like China and India and industrialized ones like Great Britain and the United States also face threats from indoor air pollution. This human health hazard is less familiar to most of us than outdoor air pollution, but statistically it is more dangerous.

Indoor Air Pollution

Indoor air generally contains higher concentrations of pollutants than does outdoor air. As a result, the health effects from indoor air pollution in workplaces, schools, and homes outweigh those from outdoor air pollution. One estimate, from the United Nations Development Programme in 1998, attributed 2.2 million deaths worldwide to indoor air pollution and 500,000 deaths to outdoor air pollution. Indoor air pollution alone, then, takes roughly 6,000 lives each day.

If this seems surprising, consider that the average U.S. citizen spends at least 90% of his or her time indoors. Then consider that in the past half century we have manufactured and sold a dizzying array of consumer products, many of which we keep in our homes and offices and have come to play major roles in our daily lives. Products as diverse as insecticides, cleaning fluids, plastics, and chemically treated wood all exude volatile chemicals into the air we breathe.

Risks differ in developing and developed nations

Indoor air pollution has the greatest impact in the developing world, where poverty forces millions of people to burn wood, charcoal, animal dung, or crop waste inside their homes for cooking and heating with little or no ventilation (Figure 13.14). In the process, they inhale dangerous amounts of soot and carbon monoxide. In the air of such homes, concentrations of particulate matter are



FIGURE 13.14 In the developing world, many people build fires inside their homes for cooking and heating, as seen here in a South African kitchen. The fires expose family members to particulate matter and carbon monoxide. In most regions of the developing world, indoor air pollution is estimated to cause upwards of 3% of all health risks.

commonly 20 times above U.S. EPA standards, the World Health Organization (WHO) has found. Indoor air pollution from fuelwood burning, the WHO estimates, kills 1.6 million people each year, comprising over 5% of all deaths in some developing nations and 2.7% of the entire global disease burden.

Whereas particulate matter and chemicals from wood and charcoal smoke are the primary indoor air health risks in the developing world, the top risks in developed nations are cigarette smoke and radon. The health effects of smoking cigarettes are well known, and inhaling secondhand smoke causes many of the same problems, ranging from irritation of the eyes, nose, and throat, to exacerbation of asthma and other respiratory ailments, to lung cancer. Tobacco smoke is a brew of over 4,000 chemical compounds, many of which are known or suspected to be toxic or carcinogenic.

Fortunately, the popularity of smoking has declined in developed nations, and many venues now ban smoking. In London, people are debating whether to ban smoking in pubs. The health benefits of doing so are clear, but pubs are such a traditional feature of British life that any change in custom is bound to be controversial.

Radon is the second-leading cause of lung cancer in the developed world, responsible for an estimated 20,000 deaths per year in the United States alone. As we saw in Chapter 10 (• p. 215), radon is a radioactive gas resulting from the natural decay of uranium in soil, rock, or water, which seeps up from the ground and can infiltrate buildings. Radon is colorless and odorless, and it can be impossible to predict where it will occur without knowing details of an area's underlying geology. As a result, the only way to determine whether radon is entering a building is to measure radon with a test kit. Testing in 1991 led the EPA to estimate that 6% of U.S. homes exceeded the EPA's maximum recommended level for radon. Since the mid-1980s,

18 million U.S. homes have been tested for radon, and 700,000 have undergone radon mitigation. Many new homes are now being built with radon-resistant features.

Many substances pollute indoor air

In our daily lives at home, we are exposed to many indoor air pollutants (Figure 13.15). The most diverse indoor pollutants are VOCs. These airborne carbon-containing compounds are released by everything from plastics to oils to perfumes to paints to cleaning fluids to adhesives to pesticides. VOCs evaporate from furnishings, building materials, color film, carpets, laser printers, fax machines, and sheets of paper. Some products, such as chemically treated furniture, release large amounts of VOCs when new and

progressively less as they age. Other items, such as photocopying machines, emit VOCs each time they are used. The VOC formaldehyde—widely used in pressed wood, insulation, and other products—irritates mucous membranes, induces skin allergies, and causes other ailments.

VOCs are often held responsible for *sick-building syndrome*, an illness produced by indoor pollution in which the specific cause is not identifiable. Besides VOCs, microorganisms such as bacteria, fungi, and mold can induce allergic responses and cause building-related illness. Heating and cooling systems in buildings make ideal breeding grounds for microbes, providing moisture, dust, and foam insulation as substrates, as well as air currents to carry the organisms aloft. The U.S. Occupational Safety and Health Administration (OSHA) has estimated that

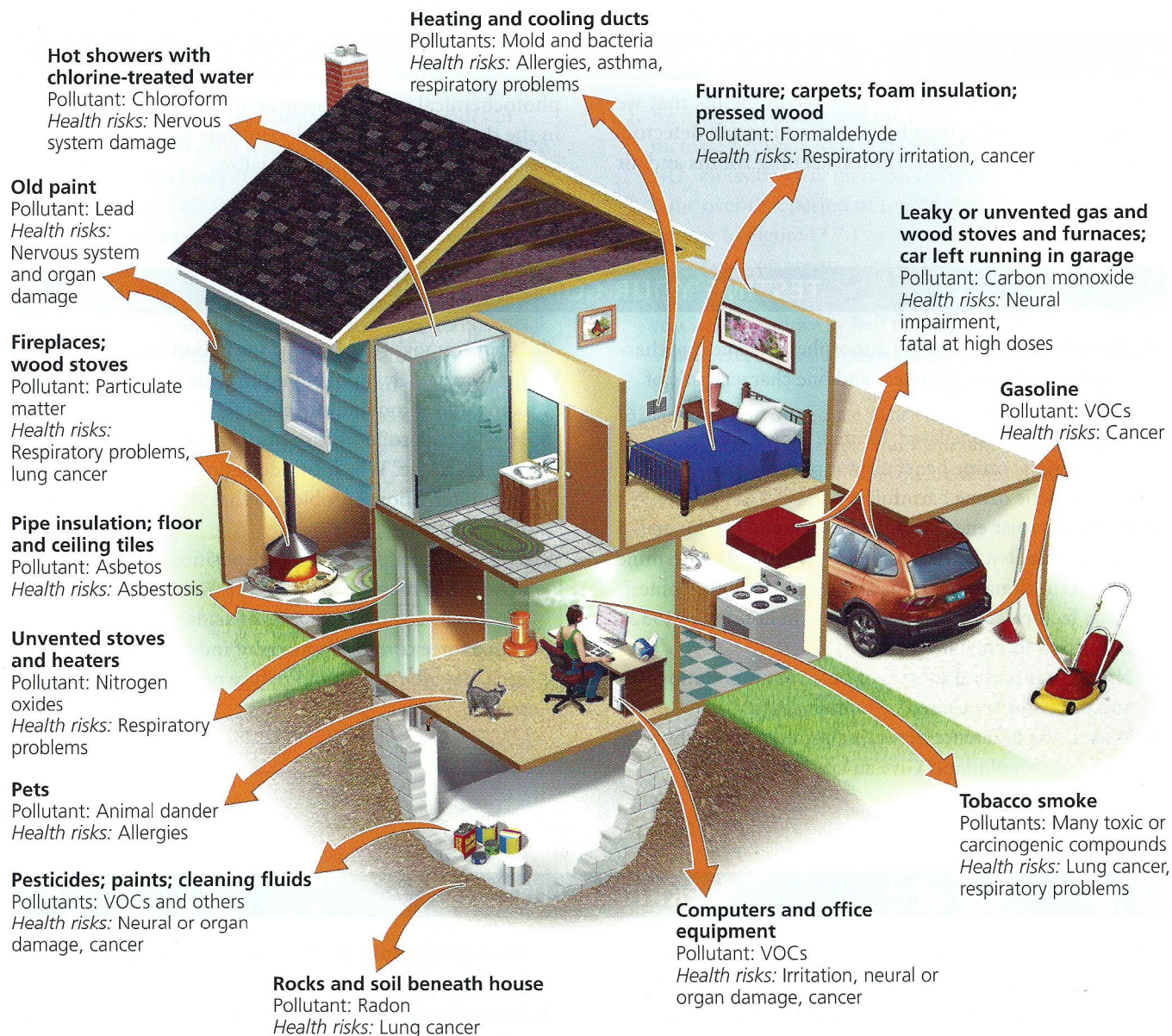


FIGURE 13.15 The typical U.S. home contains many sources of indoor air pollution. Shown are common sources, the major pollutants they emit, and some of the health risks they pose.

30–70 million Americans have suffered ailments due to the environment of the building in which they live.

Weighing THE ISSUES | How Safe Is Your Indoor Environment?

Think about the amount of time you spend indoors. Name some potential indoor air quality hazards in your home, work, or school environment. Are these spaces well ventilated? What could you do to improve the safety of the indoor spaces you use?

Using low-toxicity materials, monitoring air quality, keeping rooms clean, and providing adequate ventilation are the keys to alleviating indoor air pollution in most situations. In the developed world, we can limit our use of plastics and treated wood where possible and limit our exposure to pesticides, cleaning fluids, and other known toxicants by keeping them in a garage or outdoor shed rather than in the house. The EPA recommends that we test our homes and offices for radon and install detectors for carbon monoxide. In addition, keeping rooms and air

ducts clean and free of mildew and other biological pollutants will reduce potential irritants and allergens. Finally, it is important to keep our indoor spaces well ventilated to minimize concentrations of pollutants.

Conclusion

Indoor air pollution is a potentially serious health threat. However, by keeping informed of the latest scientific findings and taking appropriate precautions, we as individuals can significantly minimize the risks to our families and ourselves. Outdoor air pollution has been addressed more effectively by government legislation and regulation. In fact, reductions in outdoor air pollution in the United States, Great Britain, and other developed nations represent some of the greatest strides made in environmental protection to date. Much room for improvement remains, however, particularly in reducing acidic deposition and photochemical smog. Moreover, minimizing air pollution in the developing world will continue to pose a challenge as less-wealthy nations industrialize.

TESTING YOUR COMPREHENSION

1. About how thick is Earth's atmosphere? Name one characteristic of the troposphere and one characteristic of the stratosphere.
2. Where is the "ozone layer" located? How and why is stratospheric ozone beneficial for people, and tropospheric ozone harmful?
3. How does solar energy influence weather and climate? How do Hadley, Ferrel, and polar cells help to determine long-term climatic patterns and the location of biomes?
4. What factors led to the deadly smog in London in 1952? Describe a thermal inversion.
5. Name three natural sources of outdoor air pollution and three sources caused by human activity.
6. What is the difference between a primary pollutant and a secondary pollutant? Give an example of each.
7. What is smog? How is smog formation influenced by the weather? By topography? How does photochemical smog differ from industrial smog?
8. How do chlorofluorocarbons (CFCs) deplete stratospheric ozone? Why is this depletion considered a long-term international problem? What was done to address this problem?
9. Why are the effects of acidic deposition often felt in areas far from where the primary pollutants are produced? List three impacts of acidic deposition.
10. Name three common sources of indoor pollution. For each, describe one way to reduce one's exposure to this source.

SEEKING SOLUTIONS

1. Name one type of natural air pollution, and discuss how human activity can sometimes worsen it. What potential solutions can you think of to minimize this human impact?
2. Describe how and why emissions of major pollutants have been reduced by over 50% in the United States since 1970, despite increases in population and economic activity.
3. International regulatory action has produced reductions in CFCs, but other transboundary pollution issues, including acidic deposition, have not yet been addressed as effectively. What types of actions do you

feel are appropriate for pollutants that cross political boundaries?

4. **THINK IT THROUGH** You have just been elected mayor of the largest city in your state. Your city's residents are complaining about photochemical smog and traffic congestion. Traffic engineers and city planners project that population and traffic will grow by 20% in the next decade. A citizen's group is urging you to implement a congestion-charging program like London's, but businesses are fearful of losing money if shoppers are discouraged from visiting. Consider the particulars of your city, and then decide whether you will pursue a congestion-charging program. If so, how would you do it? If not, why not, and what other steps would you take to address your city's problems?

5. **THINK IT THROUGH** You have just become the head of your county health department, and the EPA has informed you that your county has failed to meet the national ambient air quality standards for ozone, sulfur dioxide, and nitrogen dioxide. Your county is partly rural but is home to a city of 200,000 people and 10 sprawling suburbs. There are several large and aging coal-fired power plants, a number of factories with advanced pollution-control technology, and no public transportation system. What steps would you urge the county government to take to meet the air quality standards? Explain how you would prioritize these steps.

CALCULATING ECOLOGICAL FOOTPRINTS

According to EPA data, emissions of nitrogen oxides in the United States in 2002 totaled 21,102,000 tons. Nitrogen oxides come from fuel combustion in motor vehicles, power plants, and other industrial, commercial, and residential sources, but fully 11,452,000 tons of the 2002 total came from the transportation sector. Of this amount, 7,365,000 tons came from on-road vehicles, with 3,583,000 tons of this total coming from light-duty cars and trucks. The U.S. Census Bureau estimated the nation's population to be 288,368,698 at mid-year in 2002 and projected that it will reach 308,936,000 by mid-2010. Considering these data, calculate the missing values in the table below (1 ton = 2,000 lb).

	Total NO _x emissions (lb)	NO _x emissions due to light-duty vehicles (lb)
You		
Your class		
Your state		
United States		

Data from U.S. EPA.

1. By what percentage was the U.S. population projected to increase between 2002 and 2010? Do you think that NO_x emissions will increase, decrease, or remain the same over that period of time? Why? (You may want to refer to Figure 13.7.)
2. Assuming you are an average American driver, how many pounds of NO_x emissions would you prevent if you were to reduce by half the vehicle miles you travel? What percentage of your total NO_x emissions would that be?
3. How might you reduce your vehicle miles traveled by 50%? What other steps could you take to reduce the NO_x emissions for which you are responsible?