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Marquita K. Hill
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Understanding Pollution

> *[t]he privilege of possessing the earth entails passing it on, the better for our use, not only to immediate posterity, but to the Unknown Future, the nature of which is not given us to know.*
>
> Aldo Leopold, forester and author[1]

This chapter speaks to humanity's massive impacts on Earth's environment while also addressing basic concepts of pollution and its impacts. Section 1.1 opens with a brief introduction to the period in which we now live, widely called the Anthropocene because of humanity's great impact. Examples are given of how we could identify the beginning of this epoch thousands of years from now. Section 1.2 introduces pollution and presents examples of pollution, how it happens, how pollutants are transported in the environment, and how they are degraded. Section 1.3 provides an example of catastrophic pollution, but then considers whether even tiny amounts of pollution are a concern. Section 1.4 discusses *nature's services* and our absolute dependence on those services, before Section 1.5 homes in on one critical natural service: that provided by Earth's soil. In Section 1.6 we ask about root causes of pollution – population, consumption, and technology. Section 1.7 asks us to face ourselves, to see that our personal actions have consequences, and to accept that we need to be part of the solution. Section 1.8 addresses the critical concept of living within our planet's boundaries, and within this section Table 1.3 summarizes nine life-support systems. Section 1.9 provides a brief overview of the large-scale burning of fossil fuels worldwide, which is a major factor keeping humanity too close to, or beyond, several of the planetary boundaries discussed in Section 1.8. Here, Table 1.4 provides a summary of pollutants produced by fossil fuels and the problems they contribute toward. Section 1.10 presents the conclusion to the chapter.

Throughout this book we see the cycling of chemicals and elements as they move continuously through different life forms and the physical environment. Note 2 at the end of this chapter presents several sources of information that you may find useful in this regard.[2]

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1.1 The Anthropocene

You are doubtless familiar with the term **global warming**. It is associated with increased levels of heat-trapping gases in the atmosphere, especially **carbon dioxide** (CO_2), much of which results from fossil fuel burning. We discuss global warming in later chapters, as well as many other ways that humans are contributing to striking environmental changes. The sentence "Humans are massively changing the Earth," is accurate. It has led to the use of the term **Anthropocene** – the age of humans – to describe the current era.

If the Anthropocene were a geological epoch, it would have a particular start point.[3] That point would be a **signal event** that occurs globally, one that would be recorded in deposits (sediments, soils, rocks) that could be observed as part of a geological record. However, there is no boundary between rock layers that might indicate when humanity's profound impacts began. That's not surprising because, when speaking of the Anthropocene, we are referring to a short period of time beginning perhaps in the mid-twentieth century. In contrast, a geological epoch is defined by evidence in rock layers, spanning millions of years. Still, Anthropocene is a very useful word to describe our great impacts on Earth, and it will be used in this text. Furthermore, it is believed that evidence of the Anthropocene will still be detectable millions of years from now.

What profound impacts on the Earth have humans had, especially in the past century, that could mark the signal event for the beginning of the Anthropocene? Candidates include:

1. *Radioactive particles* in fallout from atmospheric testing of nuclear weapons. The first atmospheric tests of a nuclear bomb began in 1945, but the fallout was mostly local. It was in 1952, when 1000 times more powerful thermonuclear bombs were exploded that we saw fallout of *artificial* radionuclides worldwide.[4] A major radionuclide in the fallout is plutonium 239 (^{239}Pu), which has a half-life of 24,110 years. It will remain detectable in the future for hundreds of thousands of years.
2. *Plastics and plastic particles*. These synthetic organic materials, which began being widely manufactured in the mid-twentieth century, are now ubiquitous in oceans and waterways.[5] Plastics are very stable and don't ordinarily biodegrade, certainly not in a predictable way. Plastics become brittle when exposed to ultraviolet (UV) light, and break down over time into smaller and smaller pieces, finally becoming microscopic particles. In protected sediments, away from UV light, they last indefinitely. Unlike nuclear isotopes, we cannot calculate exact life spans for these particles. The distribution of plastics is not evenly spread over space and time.
3. *Black carbon (BC), carbonaceous particles, and inorganic ash in sediments*.[6] These are very stable products of incomplete combustion of biomass and fossil fuels. BC is a major component of soot, while inorganic ash is the residue from burning. Wild fires have always produced such particles, which were regionally dispersed. But, especially in the past 100 years, mass burning of fossil fuels has greatly increased worldwide, as has burning of biomass. Elemental carbon (charcoal particles) is chemically very stable and very long-lived in the environment.
4. *Inorganic particles from construction*. Construction, which greatly increased in the twentieth century, uses immense quantities of concrete and also *refined* aluminum. Large amounts of concrete and aluminum debris end up in landfill sites.
5. *Nitrogen and phosphorus* particles. The natural levels of these chemical compounds have approximately doubled in Earth's soils over the past century due to greatly increased fertilizer use and increased amounts of animal and human waste.[7]

These five substances are candidates that could serve as signals, perhaps millions of years in the future, for the beginning of the Anthropocene epoch. The last four often involve pollution on a large scale, each of which will be discussed in later chapters. They are also all chemical materials. However, not all candidates that could be signals of the Anthropocene are chemicals. The major and ongoing fall in Earth's biodiversity – called the **sixth extinction event** – may also be a signal. According to Johnston, "Extinction rates for birds, mammals and amphibians are similar to the five global mass-extinction events of the past 500 million years, which probably resulted from meteorite impacts, massive volcanism and other cataclysmic forces."[8] Another possible signal is something very basic: the great increases in the quantities of fossilized domestic chicken bones appearing in landfills.

1.2 Introducing Pollution

Humans are massively changing the Earth, but how is pollution involved? The five signaling events noted above all involve pollution. Except for plastics – which are totally human-made – they also have natural sources. However, in all cases, human actions have dramatically increased the levels of the five substances in the environment.

Just as a weed is "a plant out of place," a pollutant is "a chemical out of place." Oil enclosed within a tanker is not a pollutant; once spilled into the environment, it is. However,

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doing harm involves more than being "out of place." A small oil spill may have only a small impact, with circumstances dictating what will happen: If the oil is of an easily degraded type, or one that evaporates easily, or if the wind blows the spill quickly out to sea, the small spill may cause little harm. But if it comes ashore and, worse, moves into a marsh, then even a small spill can damage plant and animal wildlife.

Now consider a large oil spill. In these cases, "spill" can be too benign a word, because the results can be disastrous. BP's oil spill into the Gulf of Mexico in 2010 is the worst in US history.[9] The wellhead, 5000 feet below the surface, gushed oil for 87 days. Approximately 130 million gallons (492 million liters) spilled, creating a near-impossible clean-up job and having devastating impacts on wildlife and the gulf environment.[10]

1.2.1 Blatant Pollution

In the 1960s and 1970s, pollution in the USA, a wealthy country, was often blatant. Some rivers, especially urban rivers, were grossly polluted by industries operating nearby. Because of the "heavy oil floating, sometimes several inches thick" on its surface, Ohio's Cuyahoga River, already lifeless and stinking, caught fire at least a dozen times.[11] One fire, in 1959, burned for eight days.

Air pollution was bad too. It could literally hit you if you lived in a city, where emissions from cars, trucks, and motorbikes stung your eyes, congested your nose, caused bad headaches, and restricted your breathing. In industrial cities, soot could drift onto streets, cling to clothes, and blow into homes. Severe air pollution episodes increased hospital admissions, sometimes killing people sensitive to the pollutants. Trash was burned in open dumps. There was routine use of large quantities of pesticides, which also killed fish, birds, and other animals, and often injured people. Photos taken in the USA before an EPA existed, showing the levels of pollution, can be seen in Small's "What cities looked like before the EPA."[12]

The last 50 years has seen much improvement of the environment in industrialized countries, with cleaner air and drinking water, better sewage treatment, and safer food laws. But it took many years and many billions of dollars to achieve those results. And still some areas of well-to-do countries can be badly neglected. Consider these two examples:

- **The Appalachian Mountains.** Parts of these mountains suffer major destruction and pollution from mountaintop-removal mining. This mountain-top removal leaves flat, moon-like expanses of land behind, with as much as 700 feet of the mountain-top blasted away to reach coal seams. The rocky debris is shoveled away by huge machines and dumped into the valleys below, destroying or badly polluting many streams.
- **Shanghai.** This is one of the wealthiest cities in China, but provides an example of wealth not protecting people from pollution.[13] Shanghai was once known for its good air quality, but began to lessen its efforts to maintain its good air pollution controls. When industries polluted, Shanghai issued only light fines, too small to deter further polluting activities. Water quality suffered also. Some water was too poor even for industrial use, let alone farm use. The city had planned to improve sewage and urban wastewater treatment, but let those plans fall way behind schedule. Shanghai's landfills were poorly maintained as they aged. Leachate from the garbage seeped into the water supply. In 2013, the city ordered hundreds of polluting facilities to close, but these orders were ignored and there were no repercussions. China's central government has good environmental laws, but a major problem – and not only in Shanghai – is that local governments resist those laws. They want the revenue they receive from polluting industries, and they want to protect jobs. Finally, in 2016, teams of central government inspectors with special powers of enforcement began fanning out across China to enforce compliance.

1.2.2 Why Pollution Happens

Unless you assume that people and industries deliberately pollute, why does pollution happen? It happens because no process is 100 percent efficient. Consider your own body – it cannot use 100 percent of the food you eat. The gastrointestinal (GI) tract does not break down the fiber in the food you eat; it is excreted from the body as solid waste. Enzymes in the gut do break down other foods into molecules that can cross the GI wall into the bloodstream, which carries the nutrition throughout your body. But the body cannot use 100 percent of the nutrient value, and a portion is excreted through urine as water-soluble waste. Also, your body cannot convert all the potential energy in food into useful energy – part of the energy is wasted. However, as you will see later, human and animal wastes can enter the environment in dangerous amounts.

As with your body, no process – natural or human-made, such as manufacturing or fuel burning – is 100 percent efficient: Each produces pollution and waste, as well as waste energy (see Box 1.2). Lack of prevention, carelessness, and unwillingness to invest in good technology, or lack of appropriate technology, worsens the levels of waste and pollution produced. Architect William McDonough and chemist Michael Braungart state that "Pollution is a symbol of design failure." In other words, pollutants need not be pollutants and solid wastes need not be wastes. Ideally, we should be able to prevent the pollution, or to return the would-be pollutants to the manufacturing

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process, or at least make sure the wastes can biodegrade harmlessly in the environment.

Almost any substance – synthetic or natural – can pollute. However, it is synthetic and other industrial chemicals that most concern people and that are emphasized here. If we learn that industrial chemicals in a water body are obviously impairing the ability of the life forms within that water to reproduce, or include a chemical such as mercury, which makes it unsafe for humans to eat the fish caught there, we all agree that the water is polluted. But what if only tiny amounts of industrial chemicals are present and living creatures apparently are unaffected? Is the water polluted? Some would say "yes," arguing that chronic effects could result – that is, adverse effects resulting from long-term exposure to even very low concentrations of a substance (Box 1.1).

BOX 1.1 TERMS USED TO DESCRIBE POLLUTANT CONCENTRATION

ppm = parts per million[a]
ppb = parts per billion (one thousand times smaller than ppm)
ppt = parts per trillion (one million times smaller than ppm)
ppq = parts per quadrillion (one billion times smaller than ppm)
To grasp these concentrations, consider the following:
- 1 ppm = 1 pound contaminant in 500 tons (1 million pounds)
- 1 ppb = 1 pound of contaminant in 500,000 tons
- 1 ppt = 1 pound of contaminant in 500,000,000 tons
- 1 ppq = 1 pound of contaminant in 500,000,000,000 tons

For a different perspective, think about periods of time:
- 1 ppm is equivalent to 1 second in 11.6 days
- 1 ppb is equivalent to 1 second in 32 years
- 1 ppt is equivalent to 1 second in 32,000 years
- 1 ppq is equivalent to 1 second in 32,000,000 years.

[a] ppm, ppb, etc. refer to parts by weight in soil, water, or food. In air, they refer to parts per volume.

Also see: Boguski, T.K. Understanding Units of Measurement. *Center for Hazardous Substances Research, Environmental Science and Technology Briefs for Citizens*, **2**, October 2006, https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.files/fileID/14285

Waste does not mean the same as **pollutant**. Waste refers to material such as garbage, trash, construction debris, and other materials at the end of their useful lives, or to bodily waste, especially feces and urine. It is also used when referring to waste heat. Gasoline is a good example of a substance that releases pollutants and produces waste heat (see Box 1.2).

1.2.3 Two Natural Laws

One natural law tells us that *matter* is neither created nor destroyed. So we know that the hydrocarbons and other substances in gasoline, as discussed in Box 1.2, do not disappear. They are converted to CO_2, water, and pollutants. The O_2 that reacts with substances in gasoline is also conserved, with most being converted to CO_2. A second natural law tells us that *energy* is neither created nor destroyed. As gasoline burns, only a small portion of its energy is actually transformed into the mechanical energy that powers the engine. The rest is "lost" as heat, but it can be considered to be dissipated rather than "lost" – under certain circumstances, waste energy can be captured and used.

1.2.4 Any Chemical or Material Can Pollute

Pollution remains conspicuous, especially in very poor countries. And pollution, now well controlled in richer countries, could become conspicuous again in places like the USA if the laws and regulations are relaxed. Already, the USA, once an environmental leader, has been abandoning that role in the twenty-first century. The US Environmental Protection Agency (EPA) has been losing staff and the ability to carry out some of its earlier functions. Political pressure may force more losses from this agency. Each state in the USA also has its own environmental agency to take up part of the slack, but there are many issues that involve many states.

Natural Pollutants

This book emphasizes anthropogenic pollutants (i.e., pollutants produced by human activity), but natural chemicals can also pollute. This happens dramatically when an erupting volcano spews out huge quantities of rocks, ash, chlorine, sulfur dioxide, and other chemicals. Sometimes human actions allow natural substances to reach dangerous levels, such as in the following examples:

- **Radon** is a naturally radioactive chemical, a gas that arises from transformations occurring in underlying rocks and soil around the world as natural radioactive uranium decays. But levels of radon in outside air are low. It is when radon seeps up into – and concentrates in – human structures that problems arise. The US EPA ranks radon, associated

BOX 1.2 **GASOLINE COMBUSTION**

Gasoline is primarily composed of *hydrocarbons* (molecules containing hydrogen and carbon), but it also contains contaminants. During combustion, the hydrocarbons are converted into the products shown below, and subsequently released via the vehicle's exhaust. Waste energy is released as heat. Almost all the reactions shown involve atmospheric oxygen (O_2).

When gasoline's hydrocarbons react with oxygen during combustion, the carbon in hydrocarbons becomes carbon dioxide (CO_2, a gas) and the hydrogen in hydrocarbons → water (H_2O).

Combustion in a gasoline engine is far from 100 percent efficient, so the reaction is:

$$\text{hydrocarbons} + O_2 \rightarrow CO_2 + H_2O + \text{incomplete products of combustion},$$

with these incomplete products including carbon monoxide (CO), soot (tiny BC particles*), volatile organic chemicals (VOCs), and lesser amounts of other chemicals, including polycyclic aromatic hydrocarbons (PAHs).[14]

Metal and sulfur contaminants in the gasoline also react with atmospheric O_2, so:

- Metals + O_2 → metal oxides in the form of tiny particulates;[15]
- Sulfur + O_2 → sulfur dioxide (SO_2), a gaseous pollutant, which becomes a particulate.

The *nitrogen oxides* (NO_x) found in motor vehicle exhaust arise differently. Nitrogen (N_2) is not a contaminant of gasoline, but combustion occurs in an N_2-heavy atmosphere in the presence of O_2. The N_2 in the air we breathe is inert, but at high combustion temperatures some of it reacts with atmospheric O_2 and the reaction products are emitted in vehicle exhaust:

$$N_2 + O_2 \rightarrow NO_x \text{ (gaseous pollutants)}$$

Most N_2 is released unchanged in the car's exhaust.[16]

* Particulates and aerosols are discussed in Chapter 5.

with human lung cancer, as second only to environmental tobacco smoke as an environmental health risk.[17]

- **Arsenic** is a natural substance that is also a **toxic** chemical (see Table 3.1 for definitions of **toxicant** and similar words). It sometimes occurs at high concentrations in certain geographic formations, especially beneath the surface. In the 1980s, arsenic poisoning became the unexpected consequence of solving a different problem: drinking water contaminated by infectious microbes. Millions of borehole wells were drilled in Bangladesh, India, and other countries to provide clean drinking water. It took some time before people realized that the new water source was poisoning them. Arsenic, present in the rock and soil into which the wells were drilled, was dissolving into the well water. The result has been a massive and ongoing poisoning in which millions suffer from arsenic poisoning. See Section 11.2.1 for more on this.
- **Asbestos** is another dangerous naturally occurring substance, and chronic exposure to asbestos leads to respiratory diseases and cancer. In El Dorado County, California, it was population growth that led to homes being built in new regions, including areas rich in asbestos deposits. Subsequently, asbestos exposure became a major concern. In certain regions of Turkey, asbestos is also found in high concentrations. In the USA, until 1986, when exposure limits were placed on asbestos in the workplace, asbestos was a common workplace pollutant.[18]

1.2.5 Human-Produced Pollution

"I am, therefore I pollute" is a statement applying to a multitude of processes. Consider all of the following and how they contribute to pollution: motor vehicles, including cars, buses, trucks, and off-road vehicles; long-haul transport, such as airplanes and ships; chemical and petroleum refineries; manufacturing facilities; commercial operations, including dry cleaners, bakeries, and garages; power plants generating electricity by burning coal, oil, or natural gas; agricultural operations growing crops or raising animals; food-processing operations; mining; construction and road building; military operations; forestry operations; municipal operations, including provision of drinking water, wastewater treatment, and road maintenance; activities occurring in commercial and municipal buildings, and in private dwellings, including consumer product use.

Road building is an example of a major and ever-increasing source of pollution, and often also of severe environmental damage. The soil under a road is "polluted," simply by being sealed off from any natural use, or other human use, such as agriculture. The land around the road is susceptible to runoff, carrying away soil and other pollutants that human activity has brought in. The soil itself, when found in runoff, is a pollutant. Forests are often damaged or destroyed to make way for roads, leading to further pollution, and these roads then allow polluting motor vehicles to enter new places. This opening up of the landscape also makes it available for mining and other polluting activities.

Obviously, roads are useful – and often necessary – and some negative impacts can be avoided. Kovacevic's article, "Road networks can spread like 'cancer' into ecosystems, with devastating effect,"[19] discusses recommendations to protect biodiversity. We cannot – often do not want to – stop road building. However, environmental protections can be provided.

As population grows, so does pollution. And in prosperous locales, consumption per individual typically grows too, and technologies become more widely used and advanced. An introduction to types of pollutants is seen in Table 1.1.

Table 1.1 **An introduction to types of pollutants**

Category	Examples
Organic chemicals	Polychlorinated biphenyls (PCBs), oil, many pesticides
Inorganic chemicals	Salts, nitrates, metals, and their salts
Organometallic chemicals	Methylmercury, tributyltin, tetraethyl lead
Acids[a]	Sulfuric, nitric, hydrochloric, acetic acids
Physical[a]	Eroded soil, trash
Radiological[a]	Radon, radium, uranium
Biological	Microorganisms, pollens

[a] Acids, as well as physical and radioactive pollutants, can be either organic or inorganic – *sulfuric acid is inorganic*. *Acetic acid* (found in vinegar) *is organic*. Biological pollutants are mostly organic, but often contain inorganic components.

1.2.6 Pollutant Movement and Transport

The concentration of a pollutant is greatest at or near the point of emission. However, pollutants *move*. Depending on the pollutant in question, it can move in a number of ways. First, consider a situation in which the pollutant moves – as is often the case – in more than one medium. The highly toxic and long-lived *dioxins* are often emitted as particulates from an incinerator. The highest fallout is onto vegetation, soil, and water near the incinerator. However, some particulates do not fall out of the air, but are caught in air currents and can be carried long distances before settling out. Wherever the dioxins fall, they may contaminate forage or grain that is eaten by cattle and other animals, and the fat-soluble dioxins are absorbed into the animal's fat. Humans eating fatty meat such as hamburgers then absorb dioxins into their own fat. The long-lived fat-soluble dioxins, once stored in fat, may stay for years. Storage in tissue does eventually end – dioxins are slowly broken down over years and excreted from the body.

Water Transport

Figure 1.1 shows sources of water pollution. Common pollutants found in rivers include untreated or poorly treated sewage. Plastic pollutants are increasingly common, and

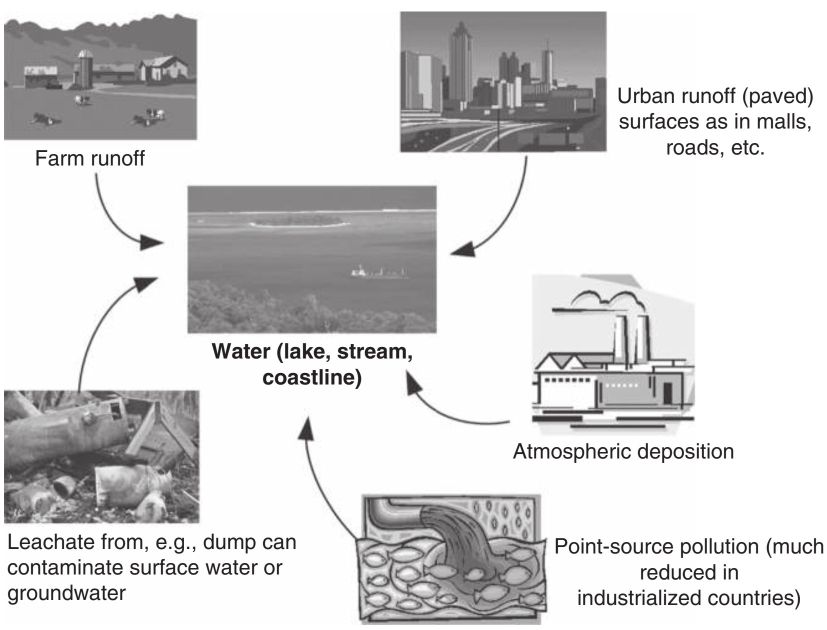

Figure 1.1 Sources of water pollution.

very often flow with a river to be carried into the ocean. Once in the ocean they can travel thousands of miles (see Chapter 10). Two disastrous examples of this are the following:

- In the year 2000, a major spill of waste – containing cyanide and hazardous metals from a gold-mining operation – occurred in Romania.[20] The waste overflowed the dam behind which it was stored and spilled into the Danube River, which joins the Tisza River flowing into Hungary and Yugoslavia. Although the spill was diluted by the rivers' water, it still had deadly effects. One Yugoslav mayor said that 80 percent of the fish in the Tisza near his town died. Another person observed: "The Tisza is a dead river. All life, from algae to trout, has been destroyed." At the time, the spill was said to be the worst environmental disaster in Europe since Chernobyl.
- In 1986 a "catastrophic fire" occurred at a Sandoz (now Novartis) chemical factory in Switzerland.[21] Chemicals, including 30 tons of pesticides, were washed into the Rhine River by firemen. These were carried along the Rhine, through France and Germany, and entered the North Sea. Along the way the poisoned water killed fish and other aquatic life.

Notice that in both incidents, national borders were crossed and harm resulted far beyond the original site of the accident.

Air Transport

When a gaseous pollutant mixes with the atmosphere after its emission, it can sometimes be carried worldwide and become a **transboundary pollutant** – that is, it crosses artificial human borders as it travels.

The best-known example of a pollutant mixing evenly in the atmosphere is *carbon dioxide*, the major contributing gas to global warming (see Chapter 7). Carbon dioxide is a stable and long-lived chemical that builds up in the atmosphere over time as emissions continue.

Many pollutants may start out as gases but, unlike carbon dioxide, are not chemically stable. Such substances undergo chemical change. The "acid rain" precursors *sulfur dioxide* and *nitrogen oxides* start out as gases but undergo reactions in the atmosphere that convert them into fine particulates (see Chapter 6). These acid particulates are transboundary pollutants and can be carried in the air for hundreds, even thousands, of miles before the particles all settle out onto land and water. For example, acid precursors originating in European countries harmed forests and lakes in Sweden to the north of where emissions occurred, while Japan suffers pollution caused by coal burning in China.

Sulfur dioxide and nitrogen oxides cannot travel worldwide from a single source – though they can travel a very long way – but their impact is still global. This is because acidic pollutants (most commonly emitted during the burning of fossil fuels) are released in so many places around the world that many sources overlap.

Another characteristic of sulfur dioxide and nitrogen oxides is that – although only small quantities of acid particulates may be emitted at any one time or from one place – continuing emissions allow them to accumulate in soil and water over time.

There are other pollutants you will encounter in this text that can also travel thousands of miles, sometimes worldwide, and have impacts at a point far from the point of emission (Box 1.3). Mercury is a well-known example of this.

Sediment Transport

Pollutants buried in sediments may not stay buried. Sediments are composed of soil, silt, minerals, and organic materials that have been carried into a water body from the surrounding land and paved surfaces. The sediment itself is, in its turn, buried by additional incoming sedimentary material. Organic pollutants are often buried

BOX 1.3 AN EXAMPLE OF TRANSBOUNDARY AIR TRANSPORT

Ground-level *ozone* (O_3) is an air pollutant injurious to humans, crops, and other plants and forests. Ozone is formed from other air pollutants (Chapter 5). US law regulates levels of ozone in the air. But what happens if significant amounts of ozone are transported into the US from foreign sources?[22] Ozone is toxic at very low concentrations: knowing this, you immediately understand that importing ozone is a problem. Now, consider further: Ground-level ozone levels have been increasing in China and nearby locales by 1–3 percent per year. This has led to increasing atmospheric transport of ozone (and of chemicals converted to ozone) into the western USA, where ozone levels are regulated. Thus, western US levels are increasing, but only because of imported ozone. So, regulating ozone in the USA is hampered because the USA cannot control the levels of the imported chemicals. Thus, state or national efforts to reduce ozone are not enough. Global efforts are also required. For a pollutant that has traveled long distances, it is often possible to discover its geographic source by examining its chemical signature.

within it. However, sediments are not reliably buried. Bottom-feeding organisms may ingest the pollutants, and thus introduce them into the food web. Also, riverine and coastal area sediments are sometimes dredged. When that happens, chemical contaminants are brought back to the surface along with the sediment. The currents of a strongly flowing river or stream can also move sediments.

Soil Transport

Pollutants in soil can likewise move. As is the case with sediments, pollutants in soil may not stay trapped. Water percolating through soil can carry pollutants down into groundwater or into a different type of soil. Rainwater can penetrate contaminated soil, and the water either dissolves the pollutants into itself or, in some cases, physically carries away pollutants, including pesticides and fertilizers. Rainwater also erodes soil that may have pollutants absorbed within it.

Biotransport

Pollutants often find their way into the foods of birds, animals, and humans. Then, **biotransport** may occur (Box 1.4), which is when pollutants are carried in body tissues of migrating animals such as salmon, whales, or birds. They may later be found in the droppings of migratory birds.

BOX 1.4 COMBINATION OF THE GRASSHOPPER WITH BIOTRANSPORT

The Grasshopper Effect

The **grasshopper effect** (or **global distillation**) is a special case of pollutant transport. The insecticide *dichlorodiphenyltrichloroethane* (DDT) provides an illustration. If DDT is used in a warm Latin American country, it evaporates and prevailing winds blow it north.[23] As DDT moves north it encounters cooler air, condenses, and lands on the ground. On a warm day, it evaporates again. The process is repeated, sometimes many times. Eventually, in the far north it is too cold for the DDT to evaporate again, so it stays put – that is, the Arctic is a *sink* for DDT and similar **persistent organic pollutants** (POPs). These are chemicals that persist in the environment, bioaccumulate, and are toxic; they are described is more depth in Chapter 14.

Persistent organic pollutants in the Arctic accumulate in soils and water, enter the Arctic food chain, and build up in the fat of marine mammals. The Inuit – the Arctic's indigenous people – eat the contaminated animals, with the result that DDT builds up in their own body fat to levels among the highest seen in the world. Worse, because DDT and other POPs concentrate in fat, high levels are found in the fatty portion of mother's milk. Thus, infants receive risky amounts of these pollutants as they nurse. Canada has been working to cut pollutant flow from the south, and in 2008 there was good news. Canadian government studies indicated that levels of PCBs, DDT, and other POPs in the flesh of Arctic animals have either leveled off or started to decline. This can probably be attributed to an international treaty that banned production and use of a number of POPs (see Chapter 14).[24]

Transport by Migrating Birds

The grasshopper effect does not totally explain DDT accumulation in the frozen north. If it did, then DDT should be evenly distributed across the Arctic. Canadian scientists actually find DDT hotspots. Sediments in certain ponds have concentrations of DDT that are 60 times higher than other nearby spots that serve as controls, along with levels of mercury – which also bioaccumulates – that are 10 times higher.[25] Investigation revealed that *contaminated droppings* of migratory seabirds (large numbers of which nest on cliffs over the ponds) were responsible for these striking observations. This happened because the DDT originates in southern regions, where it contaminates fish in coastal waters; the seabirds that eat the fish become contaminated too. Thereafter, the birds migrate to their Arctic nesting sites over Arctic ponds, where their DDT-contaminated droppings fall into the ponds. Those droppings are major sources of nutrition into Arctic pond ecosystems, promoting the growth of moss and plankton. The ponds *also* become contaminated with DDT. Insects eat the contaminated moss and plankton, and the insects are, in turn, eaten by birds and other animals. Thus, these chemicals continue to spread in the food web and in humans. This is land-based *bioaccumulation*.

1.2.7 The Fate of Organic Pollutants

Pollutants do not only move. As noted with acid rain precursors in the previous section, they can also undergo chemical reactions that convert them into other chemicals. Thus, the *fate* of a pollutant is often to be transformed into chemicals different than what was initially emitted.

Biodegradation

Almost all chemicals that contain carbon are considered *organic chemicals*, whereas *inorganic chemicals* do not. In general – but with exceptions – organic chemicals can **biodegrade** – that is, be broken down by *microorganisms*. The microbes degrade the organic portions of plant debris, animal remains, trash, and many individual pollutants. When oxygen is present and organic chemicals are degraded all the way to CO_2 and water, they are said to be **mineralized**, that is, the organic components are gone. Some microorganisms can degrade organic substances without the need for oxygen. In that case the end product is commonly *methane* ("swamp gas"), as seen when microbial degradation occurs in sediment or mud in rice paddies or marshes. Some synthetic organic chemicals have structures that make it very difficult for microbes to degrade them (see Chapter 14). These include polychlorinated chemicals such as *dioxins*, *DDT*, and *PCBs*, which sometimes persist in the environment for many years – indefinitely in very cold climates. In moderate and warm climes, biodegradation can occur in both water and soil. Long-lived – and toxic – chemicals such as *TCDD* (a dioxin) can take many years to be transformed into harmless forms by living organisms. The process leading to a pollutant's final fate can be complex.

Overwhelming the Biodegradation Process

Degradation of organic wastes is one of the vital natural services performed by microbes. However, human activities often overwhelm this natural system when great quantities of organic material are released. Food processors, tanneries, and paper mills are examples of facilities that have historically released great quantities of wastes into rivers and lakes. Although the wastes are biodegradable, the natural processes of biodegradation become overwhelmed and water quality is severely degraded. This is still the case in many places in the world.

When Biodegradation Does Not Work

A whole category of organic materials – *plastics* – are not biodegradable. To an alarming degree, plastics are reaching our waterways and the ocean. These cannot be broken down by microbes into innocuous chemicals. They are degraded by physical actions that lead to ever-smaller pieces of plastics, finally becoming so-called microplastics. This is a major problem in the oceans and the world's waterways and is discussed in Chapter 10. The fate and transport of specific chemicals are discussed in later chapters.

Other Factors Involved in Degrading Organic Chemicals

- **Atmospheric oxygen** reacts with many organic substances.
- Organic materials break down more quickly at **higher temperatures**. In very cold conditions, such as in the Arctic and Antarctic, organics may persist for many thousands of years, becoming deeply buried in snow and ice.
- **Sunlight**, especially the strong ultraviolet radiation of summer, contributes to the breakdown of organic pollutants.
- **Wave motion** in water assists degradation by bringing pollutants to the surface and exposing them to sunlight, heat, and oxygen.
- This chemical species, the **hydroxyl radical**, is vital to degrading chemicals in the atmosphere. This radical, composed of one oxygen atom and one hydrogen atom, has a free electron, which makes it a *highly reactive* species. It is the chief *oxidizing agent* in the atmosphere and is responsible for destroying organic chemicals; it can also destroy inorganic chemicals (see Chapter 5 and the Appendix).

1.2.8 The Fate of Inorganic Pollutants

Inorganic chemicals – those without carbon – are also often transported away from their points of emission. However, inorganic chemicals are already mineral substances, so obviously don't undergo mineralization. Inorganic substances *do* undergo chemical reactions that change their original chemical structure. A simple example is what happens to iron in the environment, where it is exposed to oxygen (also see Box 1.2, which explains that metals and metal compounds can be burned – *oxidized* to metal oxides). Oxidation also occurs, albeit slowly, without combustion. You may have seen a reddish bridge: the color results from the iron reacting with atmospheric oxygen to form the reddish iron oxide. If you take a sample of that iron oxide and heat it to a high enough temperature, you recover the iron while driving the oxygen back into the air. Sulfur (also discussed in Box 1.2) reacts with oxygen to yield sulfur oxides. As with iron oxides, the sulfur in sulfur oxides can be recovered.

1.3 Devastating versus Tiny Levels of Pollution

1.3.1 Pollution That Devastates

Sometimes a pollution event is so tragic that it changes our way of looking at the world. The deadly explosion that occurred in Bhopal, India is one such event. Union Carbide, an American-owned factory in Bhopal, manufactured the insecticide carbaryl. The process used *methyl isocyanate* (MIC), an extremely toxic and volatile liquid that reacts violently with water. Despite this, the factory lacked stringent measures to prevent water from ever contacting the MIC.

During the night of December 2, 1984, water entered a storage tank containing 50,000 gallons (189,271 liters) of MIC. The Indian government later said that improper washing of lines going into the tank caused the catastrophe. Union Carbide claimed that a disgruntled employee deliberately introduced water. In any case, 25–40 tons (23–36 metric tonnes) of a deadly chemical vapor settled over half of the city, exposing more than 600,000 people. About 3400 people – very possibly more – were killed overnight, and about 15,000 more died in the following days and years. Over 40 percent of those women who were pregnant at the time had miscarriages. Tens of thousands of people remained chronically ill 30 years later, suffering from respiratory infections, eye damage, neurological damage, and other ailments. The catastrophe was worsened because many people lived in homes crowded close to the factory.

Poisoned residents received little medical attention at the time of the accident, partially because physicians didn't know what compounds were in the toxic cloud so it was difficult to know the best mode of treatment. Many thousands of animals were also killed. Compensation for victims came slowly. For many years, a Bhopal court had criminal charges pending against Union Carbide's then chief executive officer, accusing him of having consciously decided to cut back on safety and alarm systems as cost-cutting measures. In 1984 Union Carbide had almost 100,000 employees, but almost went out of business; by 1994 it employed only 13,000. The plant site has never been more than partially cleaned up.[26]

1.3.2 Tiny Levels of Contaminants

Bhopal represents horrendous pollution. But what are we to think about levels of pollutants so low that they are barely detectable – are such levels risky? Modern analytical chemistry is so sensitive that synthetic organic chemicals can be detected almost anywhere – in soil, water, air, food, animals, plants, and in our own bodies. So how are we to think about such situations?

Consider hypothetical contamination: Assume that tiny amounts of 20 different synthetic chemicals have been detected in a local lake. Each is present in an amount so tiny that it alone is highly unlikely to cause a problem. Moreover, many of these 20 chemicals are also found, likewise in tiny amounts, in our bodies. Should we be concerned?Possibilities that could increase your concern include the following:

- Among the 20 contaminants considered here are chemicals that are very similar to one another. Similar chemicals may exert toxic effects in similar ways; if the levels of each are added together they could potentially pose a problem. Organophosphate pesticides are an example of this. There are many different organophosphates, but each exerts toxicity in a similar way. In the lake scenario, if several of the contaminants are organophosphates then the total concentrations added together could cause concern.
- Even if none of the chemicals act similarly in the body, perhaps some combination of them could exert a **synergistic** effect – that is, one chemical could magnify the effect of another chemical out of all proportion to its concentration. Testing for synergistic effects among 20 chemicals is almost impossible because we could not reasonably test them in all possible combinations.
- Species differ widely in their sensitivity to toxicants. One species may be many times more sensitive than another. There is also a range of sensitivities within any individual species, including humans.

Possibilities that could decrease your concern include the following:

- Two chemicals may exert **antagonistic effects** – that is, one may inhibit the toxicity of another, lessening the chance of an adverse effect. Basically, one chemical acts as an *antidote* to the other.
- Hundreds or thousands of chemicals are naturally present in the water and some or many may be similar chemically to the synthetic contaminants.
- Animals and humans deal with contaminants using biochemical pathways that evolved over millions of years to break down natural poisons in the environment. Our bodies have no way of knowing if a given chemical is natural or synthetic.
- A quarter-century ago, chemists probably couldn't even have detected many of these chemicals. Only now, with sophisticated analytical methods, can we even know if there are chemicals that might be of concern.

1.4 Nature's Services

1.4.1 Introduction to Nature's Services

Nature's services are those services furnished by ecosystems; they are also called **ecosystem services**. The Ecological Society of America tells us that