Chapter 1

Understanding pollution

"The economy is a wholly owned subsidiary of the environment. All economic activity is dependent upon that environment with its underlying resource base."

US Senator Gaylord Nelson on first Earth Day, 1970

What is pollution and why is it important? Why does pollution occur, and is it harmful at all levels? What happens to pollutants in the environment? What are the root causes of pollution? These are among the questions that Chapter 1 will examine. **Section I** introduces the major impacts that humans exert on Earth's natural systems while also emphasizing our profound dependence on the services provided by those systems. **Section II** examines why pollution happens, what substances are pollutants, and their sources. Traveling pollutants are described, and the effects they sometimes exert at great distances from their origin. In turn the environment modifies pollutants too, often lessening their harm, especially if levels are not too high. A catastrophic instance of pollution, an explosion at a pesticide plant in Bhopal, India is presented. The opposite extreme, the risk of pollutants in the environment at very low levels is examined too. **Section III** moves into impoverished parts of the world where pollution sometimes devastates human health. **Section IV** looks at root causes of pollution, in particular population growth, consumption, and large-scale technology. Finally, **Section V** comes home to each of us, pointing out that our actions have environmental consequences, sometimes in ways we don't suspect.

SECTION I

Humans are massively changing the Earth

As described in an article in *Science*,[1] Human domination of Earth's ecosystems, "Between one-third and one-half of the land surface has

[1] Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melilli, J. M. Human domination of Earth's ecosystems. *Science*, **277**, July, 1997, 494–99.

been transformed by human action; the carbon dioxide concentration in the atmosphere has increased by nearly 30% since the beginning of the Industrial Revolution; more atmospheric nitrogen is now fixed[2] by humanity than by all natural terrestrial sources combined; more than half of all accessible surface fresh water is put to use by humanity; and about one-quarter of the bird species on Earth have been driven to extinction . . . All . . . trace to a single cause, the growing scale of the human enterprise. The rates, scales, kinds, and combinations of changes occurring now are fundamentally different from those at any other time in history; we are changing Earth more rapidly than we are understanding it. In a very real sense, the world is in our hands and how we handle it will determine its composition and dynamics, and our fate."

Nature's services

In the past, we often did not even consider that we were changing our environment, let alone how that could affect us. In the twentieth century, many people willingly ignored gross pollution if its source was a factory on which the community depended for employment. "That's the smell of money" they might say. This still occurs in some places in the world. If it took so long to recognize that pollution could directly affect human health, think how difficult it is to recognize our total dependence on the environment.

Protecting drinking water

Recently, New York City spent over a billion dollars to buy land to its north in the Catskill Mountains in the watershed that provides drinking water to New York City. The City then restricted how the land could be used, forbidding activities that could pollute the watershed's streams and rivers. One action regulated was the application of pesticides and fertilizers on land because these substances can run off into local waters. By recognizing and protecting the Catskills' natural water filtration capability – an *ecosystem service* – the City avoided having to build a treatment plant to purify its drinking water. The plant would have cost about $6 billion, plus $300 million a year to run. The City saved itself $5 billion.

Protecting ecosystem services

New York City protects much of the land it bought from development. Why? ■ Trees and vegetation stabilize the soil preventing it from eroding during rainstorms, and being carried into Catskill streams as a pollutant. ■ On undeveloped land, soil and tree and vegetation roots absorb rainwater lessening the risk of flooding during heavy rains.

[2] Atmospheric nitrogen is dinitrogen, it is composed of two atoms of nitrogen. Such nitrogen is not reactive, and we breathe it in and out without effect. But under certain conditions, especially high combustion temperatures, nitrogen is "fixed" into chemicals such as nitrogen oxides. This fixing is environmentally very significant because plants can use nitrogen oxides (and ammonia formed industrially). This will be covered in Chapter 11.

The water is instead slowly released to streams, while another portion seeps down into and replenishes groundwater. ■ Undeveloped land acts as a home to wildlife and also provides timber, recreation and aesthetic value, and has the advantage of being cooler than cleared land. ■ Its wetland areas also provide services. Aquatic plants and microorganisms purify polluted water carried into the wetlands with runoff. They trap eroded soil, preventing it from running into streams and lakes. Wetlands provide flood protection by serving as a sink during heavy rains.[3] They also provide habitat to multiple bird and other species.

Natural services provided by urban trees

Not only rural, but city trees too provide valuable services. The organization American Forests was concerned by the loss of tree canopy in American cities. Using satellite and aerial imagery, they showed that tree cover in 20 US cities had declined 30% over three decades. This was disturbing: trees provide shade and cooling to the urban buildings they shelter; they have aesthetic value; they trap polluted storm water runoff via the soil held by their roots. And trees trap air pollutants: they trap gaseous pollutants by the stomata in their leaves; sticky or hairy leaves also filter particulates from air. Using a computer-based geographic information system American Forests first calculated how much air pollution urban trees remove, and then calculated the economic loss of cutting the trees. In Washington, DC trees lost to cutting would have removed about 354 000 lbs (over 160 000 kg) of major air pollutants including carbon monoxide, sulfur dioxide, and ozone. This lost capacity costs the city about $1 million a year in additional air pollution abatement expenses. And because cut trees were not there to trap storm water, there was a 34% increase in storm water runoff. It costs Washington, DC about $226 million per year to process the additional runoff. Fortunately, the average American city, despite its losses, still has about 30% tree cover. American Forests believes that this could reasonably be increased to at least 40%.

Other natural services

Ecosystems provide many services; a few of these services are outlined in the following. ■ Vegetation and trees absorb the greenhouse gas carbon dioxide, while releasing the oxygen necessary to our lives. ■ The atmosphere's stratospheric-ozone layer protects us from the sun's strongest ultraviolet radiation. ■ Worms and other organisms, and vegetation enhance the fertility of soils that we need for agriculture. ■ Healthy ecosystems provide insects, birds, and other animals that pollinate plants – including crop plants. Birds and some insects also reduce many agricultural pests. ■ Natural systems

[3] In a different context, coastal wetlands provide a buffer to hurricanes. There is great concern about a future hurricane hitting New Orleans, Louisiana since so many wetlands have been destroyed.

provide seafood, wild game, forage, wood, biomass fuels, and natural fibers. ■ They degrade organic wastes, both naturally produced and human-produced waste.

Box 1.1 | "Less forgiving than our planet."

Economists often argue that technology can substitute for natural life-support systems. One experiment in the ability of technology to support life is *Biosphere 2*, an enclosed man-made structure built as a model for a self-sustaining extraterrestrial colony in space. Completed in 1991 at a cost of $200 million, its 3.15 acres (1.27 ha) were a closed-off mini-Earth containing tiny biomes – a marsh from the Florida Everglades, an equatorial rain forest, a coastal desert, a savanna with a stream and grasses from three continents, an artificial mini-ocean with a coral reef, plus an orchard and intensive agricultural area. Its underbelly holds a maze of plumbing, generators, and tanks.

Eight people moved into the Biosphere 2 for 2 years. The first year went well, but in the second crops failed, and people grew thin. They became dizzy as atmospheric oxygen levels fell from 21% to 14% – a level typical of 14 000 ft (4267 m) elevation. This occurred because excessive organic matter in the soil absorbed oxygen from the air. Atmospheric carbon dioxide "spiked erratically," while nitrous oxide rose to levels that could impair brain function. Vines and algal mats overgrew other vegetation. Water became polluted. The Biosphere initially had 3800 plant and animal species. Among the 25 introduced vertebrate species, 19 died out and only a few birds survived. All the Biosphere's pollinators – essential to sustainable plant communities – also became extinct. Excitable "crazy" ants destroyed most other insects.

Much was learned from Biosphere 2, which was taken over in 1997 by Columbia University to be used as an educational facility in which Earth stewardship is fundamental to the curriculum, a place to "build planetary managers of the future." Among its research efforts are long-term studies of the effects of various levels of the greenhouse gas carbon dioxide on plant communities.

Someone noted that Biosphere 2 is less forgiving than our planet. But Earth too is a closed system, a larger version of Biosphere 2. History records examples of civilizations that failed or grew weak after having a severe impact upon their local environment. But survivors often could move on to other environments. Today, Earth's huge population cannot "move on" although many people struggle to immigrate to better locales. And people cannot, not in inexpensive ways available to everyone, substitute technology for nature's services. How does one substitute for breathable air?

Degrading human wastes

Think about *biodiversity*, the fantastic variety of species of animals, plants, and microorganisms in our world. Among these species are the insects and worms, bacteria, and fungi that degrade natural wastes and the wastes we discard – the sewage, garbage, and other organic wastes and pollutants. These waste-degrading creatures could live without us, but we cannot live without them. Some larger creatures eat wastes too – vultures are essential for scavenging dead animals in some places. Which species are absolutely vital to our lives? We

cannot answer that question, but we do know that a great many are needed to maintain ecosystem services. And we know that humanity is, through habitat destruction and disruption and pollution, destroying species at a rate perhaps 100 times faster than the natural rate of extinction. And we know that scientists increasingly emphasize that we are exceeding the capacity of some ecosystems to absorb our wastes.

Assessing Earth's ecosystems

Given that Earth's ecosystems are vital to human lives we need to know how those ecosystems are faring. What is the health of our planet? In 2000 the United Nations Environment Program (UNEP) assisted by about 1500 scientists, embarked on a worldwide study the *Millennium Ecosystem Assessment*. Costing $5 million a year over 4 years, it is evaluating how well the planet's ecosystems are functioning. The ecosystems being monitored are: forests, inland waters and coastlines, shrub lands, dry lands, deserts, agricultural lands, and others. How well are they providing the ecosystem goods and services that we expect of them including food, fiber, and clean water? How are human actions affecting their capacity to provide these services? The vitality of ecosystems is critical both to human life and health and to the economic viability of nations. The Millennium Ecosystem Assessment will provide reliable, scientifically reviewed information on strengthening how we humans can better manage ecosystems for our own use and for long-term sustainability. The assessment received a great assist in the form of 16 000 photographs donated by the US National Aeronautics and Space Administration (NASA). Taken from space by satellite, the pictures show changes occurring in the 1990s in biomes as varied as coastlines, mountains, and agricultural land.

Questions 1.1

1. What did Harvard biologist, E. O. Wilson mean when he said, "We need invertebrates but they don't need us."?
2. What services are provided by: (a) Grasslands? (b) Estuaries? (c) Soil? (d) Coral reefs? (e) Birds? (f) Bats? (g) Insects? (h) Microorganisms?
3. What pollution can result from: (a) Deforestation? (b) Grasslands loss? (c) Wetlands loss?
4. Technology can mimic some natural services, for example when we purify water, albeit often at high cost. What technology do you know of, or can you envision, that might: (a) Provide drinking water at a reasonable cost? (b) Rebuild agricultural soil damaged by erosion or by the build-up of salt? (c) Produce adequate food in the absence of fertile soil?
5. A major question that society faces is how to value nature's many services while still respecting private property. What approaches could we use to solve this major problem?

SECTION II

Pollution

When pollution is obvious

If you read that a *pollutant* is "any substance introduced into the environment that adversely affects the usefulness of a resource" you learn little. But the importance of a pollutant may be obvious if you live in a city where emissions from cars, trucks, and buses sting your eyes, congest your nose, cause your head to ache, or tighten your breathing. Thirty years ago pollution in the United States, a wealthy country, was easy to see. Rivers were often obviously polluted. Industries located on rivers often released large quantities of pollution into them. Oil floating on the surface of Ohio's Cuyahoga River caught on fire on more than one occasion; one fire in 1959 burned for 8 days. Air pollution was obvious too. Soot in industrial cities drifted onto buildings and clothing, and into homes. Severe air pollution episodes increased hospital admissions and killed sensitive people. Trash was burned in open dumps. Heavy pesticide use caused kills of fish, birds, and other animals. The new century finds the environment in industrialized countries much improved. But continuing population growth and unremitting, indeed accelerated, land development leave serious issues.

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. Spilled into the environment, however, it may be a pollutant although doing harm involves more than being out of place. A small oil spill may go unnoticed, but a large one can be disastrous. In addition, circumstances are always important: if the oil is of a type easily degraded, or if wind blows a spill quickly away from shore, there may be little harm. Blown toward shore it may devastate animal and bird populations, and sand-dwelling organisms.

Almost any substance, synthetic or natural, can pollute, but it is synthetic and other industrial chemicals that most concern people. If we learn that industrial chemicals in a water body are obviously impairing the ability of birds to reproduce, or are associated with fish tumors we all agree that the water is polluted. But what if only tiny amounts of industrial chemicals are present and living creatures apparently 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, or that even largely unnoticed effects could be negative over time. The word "waste" differs from pollutant, although waste can pollute. Waste often refers to garbage or trash. Examples include the garbage discarded by households or restaurants, or the construction debris discarded by builders, or material that has reached the end of its useful life. See Table 1.1 for a description of how pollutant concentrations are described.

Pollution may be less obvious if you live in a wealthy country where the twentieth century brought cleaner air and drinking water,

Table 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)

[a]The terms above refer to parts by weight in soil, water or food, or – in air – parts per volume.
To grasp these concentrations, consider the following:

1 ppm = 1 pound of contaminant in 500 tons, that is 1 million pounds (1 g in 1000 kg, i.e., 1 metric tonne)
1 ppb = 1 pound of contaminant in 500 000 tons (1 g in 1000 tonnes)
1 ppt = 1 pound of contaminant in 500 000 000 tons (1 g in 1000 000 tonnes)
1 ppq = 1 pound of contaminant in 500 000 000 000 tons (1 g in 1000 000 000 tonnes)

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

sewage treatment, safe food laws, and food refrigeration. But it took many years and hundreds of billions of dollars to reach those positive results. And wealth does not guarantee a healthy environment. Read a 1994 description[4] of Hong Kong, one of the Earth's wealthiest spots, "Beaches that once were crowded by fun seekers are laden with industrial debris or too polluted for swimming. Rivers not foaming from pollutants often are purple from industrial dyes; others are clogged with hazardous metals from scores of electroplating plants. Some territorial waterways have been contaminated by untreated livestock wastes, and close to 25% of its 5.5 million inhabitants suffer from respiratory problems, many due to high levels of sulfur dioxide, nitrogen oxides, and particulate emissions from vehicles . . ." Moreover, over-fishing and pollution left its waters almost devoid of fish. To make Hong Kong harbor less of an eyesore to tourists, boats collect many tons of trash a day. But its stench could not be disguised – until recently, 70% of the 1.7 million tons (1.5 million tonnes) of human sewage produced each day in Hong Kong was not treated before discharge. Only now are modern sewage-treatment plants being built as Hong Kong begins to confront seriously its many environmental problems.

Why does pollution happen?

Unless you assume that people and industry deliberately pollute, the question arises – why does pollution occur? Pollution happens because no process is 100% efficient. Consider your body – it cannot use 100%

[4] Anon. Hong Kong starts pollution clean up in earnest. *Chemical Engineering Progress*, **90**(2), February, 1994, 12–15.

of the food you eat. ■ For example, the fiber in food is not broken down in the gastrointestinal (GI) tract, and is excreted with the feces as solid waste. ■ Enzymes in the gut break down other foods to molecules that can cross the GI wall into the bloodstream. The blood carries these nutrient molecules to your organs. But organs cannot use 100% of the nutrient value, and a portion is excreted in urine as chemical waste. ■ Likewise your body cannot convert all the potential energy in food into useful energy. Part becomes waste energy. ■ No natural or human process, such as manufacturing or fuel burning, is 100% efficient. See Box 1.2. Each process produces pollution or waste and waste energy. Carelessness or poor technology aggravates the amount of pollution produced, as do poorly designed processes.

Box 1.2 | A gallon of gasoline

Gasoline contains hydrocarbons (composed of hydrogen and carbon) along with smaller amounts of contaminants. During combustion, the chemicals in gasoline are converted into the products shown below, and are released through the vehicle's exhaust pipe. Notice the involvement of oxygen (O_2) in each reaction. Waste energy is released as heat.

Hydrocarbon combustion

- Carbon reacts with atmospheric O_2 → carbon dioxide (a greenhouse gas).
- Hydrogen reacts with atmospheric O_2 → water (hydrogen oxide).

Combustion is not 100% efficient

- Hydrocarbons react with atmospheric O_2 → carbon dioxide + water. However, unless excess O_2 is present some hydrocarbons end up as *incomplete products of combustion*. These include polycyclic aromatic hydrocarbons (PAHs; see Box 5.7), organic vapors, and soot. (Soot is mostly composed of fine black particles of carbon that has not reacted with O_2 at all.) Although this does not ordinarily happen, excess O_2 can allow combustion to be almost 100% efficient; i.e., little or no incomplete products of combustion form.
- Think about a forest fire ignited by lightning. It also produces incomplete products of combustion such as the char in stumps, or dioxins.

Contaminants in gasoline react with O_2 too

- Metals react with atmospheric O_2 → metal oxides (particulate pollutants).
- Sulfur reacts with atmospheric O_2 → sulfur dioxide (a gaseous pollutant).

Gasoline contains very little nitrogen, but at high combustion temperatures . . .

- Atmospheric nitrogen reacts with atmospheric O_2 → nitrogen oxides.

Consider two natural laws. One tells us that *matter* is neither created nor destroyed.

- The matter in gasoline does not disappear. It becomes the pollutants shown above.
- The O_2 that reacted with all these substances is conserved too.

Another natural law tells us that *energy* is neither created nor destroyed.

- As gasoline burns to produce energy, only a portion of its energy powers the vehicle's engine – much is "lost" as heat to the environment. But, the energy is not "lost" although it is dissipated.

Questions 1.2

1. One gallon (3.78 l) of gasoline weighs between 5 and 6 lbs (2.3 to 2.7 kg). Explain how it emits about 20 lbs (9.1 kg) of carbon dioxide when it is burned.
2. (a) How does the sulfur in the fuel end up as sulfur dioxide? (b) How do the metals in fuel end up as metal oxides?

What substances pollute?

Almost any chemical, any substance, any material, whether generated by human beings or nature can pollute. Table 1.2 has but a few examples. Be sure to know how an organic chemical differs from an inorganic chemical, an organic pollutant from an inorganic one (Box 1.3). *Organic chemicals* even those difficult to degrade can be destroyed when conditions are right. However, *inorganic* substances although they can be converted into other compounds are not destroyed. Think about rust, iron oxide, which is very different from its parent chemicals, iron and oxygen. But the iron and the oxygen can be recovered from the iron oxide; they have not been destroyed.

Box 1.3 | A review of elements and chemicals

An "element" is the fundamental (or basic) form of matter. It is composed of atoms and cannot be further subdivided. There are 92 natural elements. Iron, gold, sodium, calcium, and carbon are examples.

A "compound" is a chemical composed of more than one atom from two or more elements. The very well-known compound water (H_2O) is a molecule composed of two hydrogen atoms plus one oxygen atom. Common table salt (NaCl) is a compound with one atom each of sodium and chlorine.

Organic chemicals

- An organic chemical contains the element *carbon*. Except for very simple organic compounds such as methane (CH_4), organic chemicals have carbon-to-carbon bonds, that is, the molecules contain more than one carbon atom. (Organic chemicals contain other elements, frequently hydrogen.) If the chemical contains only carbon and hydrogen it is called a hydrocarbon. But organic chemicals also often contain oxygen, nitrogen, sulfur, and other elements. If a carbon atom is bonded to a metal, the chemical is an *organometallic*. An example is tetraethyl lead. A natural example of an organometallic is hemoglobin (containing iron). An organic chemical can be simple, such as the methane or ethane found in

natural gas, or it may be more complicated such as a vitamin. Or, it may be much more complicated such as a protein or deoxyribonucleic acid (DNA, the genetic material).

- An organic chemical can be *synthetic*, that is, synthesized from chemicals found in feed materials such as petroleum, coal, wood, or cultures of molds or bacteria. An example of a simple synthetic chemical is formaldehyde (HCHO), which is used for purposes varying from making plastics to embalming corpses. Many synthetic chemicals, such as pharmaceutical drugs or certain vitamins, are more complicated.
- An organic chemical can be a *petrochemical* derived from crude oil or natural gas or synthesized using that oil or gas as a feed material. Most of the chemicals in petroleum are *hydrocarbons*. The methane (CH_4) in natural gas is a simple hydrocarbon. To make more complex chemicals from petroleum or natural gas other elements, such as oxygen or chlorine, may need to be added to the hydrocarbon.
- A *biochemical* is an organic chemical synthesized by microorganisms, plants, or animals. Proteins, fats, and carbohydrates are biochemicals. Some organometallic chemicals are also made in nature, including hemoglobin (containing iron) or vitamin B_{12} (containing cobalt). Sucrose (table sugar) and the tart-tasting acetic acid (in vinegar) are examples of simple biochemicals. Humans can synthesize many biochemicals including quite complex ones. If the structure of a chemical made by synthetic means is exactly the same as the structure found in nature, it is indeed the same chemical – the body treats both exactly the same, that is, there is no biological difference between them either.

Naturally occurring chemicals derived from natural sources can be extensively manipulated during extraction and purification and still legally be called natural. The word "natural" is often misused or used without explanation.

Inorganic chemicals

- An inorganic chemical usually does not contain carbon although a few do, such as sodium bicarbonate (baking soda) and sodium carbonate (washing soda). Inorganic chemicals may contain almost any element in the periodic table from nitrogen and sulfur to lead or arsenic.
- An inorganic chemical can be an elemental chemical such as elemental iron, or elemental mercury or tin.
- Many inorganic chemicals are found in nature such as the salts in the ocean, minerals in the soil, the silicate skeleton made by a diatom, or the calcium carbonate skeleton made by a coral.
- As is the case for many organic chemicals, many inorganic chemicals can also be made synthetically. Simpler inorganic chemicals can be manipulated to make more complicated ones. However, the total number of inorganic chemicals is much smaller than the number of organic chemicals.

Natural pollutants

This book emphasizes human-generated pollutants, but natural chemicals pollute too. This happens most dramatically when a volcano erupts, spewing out huge quantities of ash, chlorine, sulfur dioxide,