Second Edition

Understanding Environmental Pollution

Marquita K. Hill

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Understanding Environmental Pollution

A Primer

Understanding Environmental Pollution systematically introduces pollution issues to students and others with little scientific background. The first edition received excellent reviews, and the new edition has been completely refined and updated.

The book moves from the definition of pollution and how pollutants behave, to air- and water-pollution basics, pollution and global change, solid waste, and pollution in the home. It also discusses persistent and bioaccumulative chemicals and pesticides, and places greater emphasis on global pollutants. The relationship between energy generation, its use, and pollution is stressed, as well as the importance of going beyond pollution control, to pollution prevention. Impacts on human and environmental health are emphasized throughout. Students are often invited to come to their own conclusions after having been presented with a variety of opinions.

This textbook provides the basic concepts of pollution, toxicology, and risk assessment for non-science majors as well as environmental-science students.

MARQUITA HILL developed a number of environmental courses at the University of Maine, including “Issues in Environmental Pollution,” an interdisciplinary introductory course, and “Pollution Prevention and Industrial Ecology” in the Department of Chemical Engineering. She was for 7 years a visiting scholar in Environmental Health at the Harvard School of Public Health, and was a founding member and the first president of the Green Campus Consortium of Maine, an organization devoted to finding sustainable means of management for the state’s institutions of higher learning.

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This book is dedicated with love and gratitude to my husband, John C. Hassler, and to our children Evan Samli, Matthew Hassler, and Cynthia Filgate.

Contents

Preface

Understanding Environmental Pollution has been updated and almost completely revised. The book summarizes the basics of pollution, working to use language understandable to those with limited science background, while remaining useful to those with more. The impacts of pollution on environmental health receive greater attention in this edition, and there are more case descriptions, which pose reflective questions to the reader. The second edition also has greater emphasis on pollution problems in less-developed nations. It often delves too into pollution that moves beyond national boundaries. In addition, more references are included at the end of chapters, including many web sites.

A framework: Chapters 1 through 4 provide basic information on pollution, the issues that it poses, and on reducing pollution. They also discuss concepts important to later chapters. Chapter 1 introduces basic concepts in pollution, and addresses how humans are affecting the environment's ability to provide "natural services." Chapter 2 describes "comparative risk assessment," and overviews how society deals with risks. The waste-management hierarchy with its stress on pollution prevention is introduced here too, as is industrial symbiosis, treating wastes as resources. Chapter 3 introduces toxicity and factors affecting whether a chemical will have adverse effects. Chapter 4 emphasizes that exposure must occur before a chemical poses a risk, and describes how chemical risk is evaluated.

Pollution basics: Chapter 5 delves into the major pollutants in ambient air, the concerns that they pose, their sources, and efforts to reduce their emissions. Chapters 6, 7, and 8 examine global-change issues that originate with air pollution – acid deposition, global climate change, and stratospheric-ozone depletion. Chapter 9 examines major water pollutants, problems that they cause, their sources and actions to reduce emissions. The "nitrogen glut" is also overviewed, a problem now of global dimensions. Chapter 10 inspects drinking-water contaminants with an emphasis on pathogenic organisms, especially in less-developed countries. Chapter 11 summarizes the basics of the enormous quantities of solid waste that we produce, and Chapter 12 does the same with hazardous waste.

More detail: Because so many pollution problems originate with the way we produce and use energy, Chapter 13 is devoted to this issue. It also examines alternative sources of energy, which often have their own problems. Chapter 14 introduces "PBTs," organic chemicals that are persistent, that bioaccumulate, and are toxic too. Chapter 15 examines metals, many of which are also PBTs. As Chapter 16 summarizes, pesticides are pollutants of continuing concern, but alternatives to synthetic pesticides often raise their own problems. Chapter 17 focuses on pollution closer to home, the pollutants that concentrate within our households. Chapter 18 ends the book on the hopeful theme of Zero waste, zero emissions. While society must continue to grapple with the basics of pollution control and pollution prevention, others are going further. Some businesses, cities, even whole countries aim for an ideal of zero waste, zero emissions and work toward making resources out of what are now wastes.

Acknowledgements

Much gratitude goes to my husband, Dr. John C. Hassler, who faithfully cares for my computer hardware and software. I thank Richard Hill, Professor Emeritus of Mechanical Engineering, for his thoughtful input on energy issues. I am thankful too for an extremely useful tool, the database management system, AskSam, The Free-Form Database (Seaside Software, Perry, Florida). I have faithfully used this easily searchable and evolving system for 15 years to record titles, and basic information from a multitude of articles and many books. Such a database is invaluable for a text such as this, which requires so much specific information. Recent years have also seen an explosion of useful web pages, many of which are referenced under Internet resources in each chapter. Government web pages were especially useful, the US Environmental Protection Agency, the Department of Energy, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, US Geologic Survey, and the United Nations Environmental Program.

Abbreviations and acronyms

(Chemical abbreviations are listed separately below)

AC	Alternating current
ADI	Acceptable daily intake
AIDS	Acquired immune deficiency syndrome
ATSDR	Agency for Toxic Substances Disease Registry (a US agency)
BAT	Best available technology
BOD	Biochemical oxygen demand
Bt	*Bacillus thuringiensis* (a bacterium)
Btu	British thermal unit (a unit of energy)
CAA	Clean Air Act (a US law)
CAFE	Clean Air for Europe
CDC	Centers for Disease Control and Prevention (a US agency)
CDM	Clean Development Mechanism
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) (a US law relating to hazardous-waste sites)
CPSD	Consumer Product Safety Division (a US agency)
CRT	Cathode ray tube
CSO	Combined sewer overflow
CWA	Clean Water Act
DBP	Disinfection byproduct
DC	Direct current
DfE	Design for the environment
DOE	Department of Energy (a US agency)
EIA	Energy Information Administration
EMF	Electromagnetic field
EPA	Environmental Protection Agency (a US agency)
EPR	Extended producer responsibility (also called *take-back*)
ETS	Environmental Tobacco Smoke
EU	European Union
EV	Electric vehicle
FAO	Food and Agriculture Organization (a UN agency)
FDA	Food and Drug Administration
FFDCA	Federal Food Drug and Cosmetics Act (a US law)
FFV	Flexibly fueled vehicle
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act (a US law)
FQPA	Food Quality Protection Act
GCM	General circulation model
GEO	Genetically engineered organism
GI	Gastrointestinal
GM	Genetically modified

HAB	Harmful algal bloom
HAP	Hazardous air pollutant (also referred to as toxic air pollutant)
HEPA	High-efficiency particulate air (filter)
HHW	Household hazardous waste
HPV	Human papilloma virus
INDOEX	Indian Ocean Experiment
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated pest management
IR	Infrared
kW h	Kilowatt hour
LCA	Life-cycle assessment
LD_{50}	Dose killing 50% of the animals exposed to it
MACT	Maximum available control technology
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
MEI	Maximally exposed individual
μg/l	Micrograms per liter (a concentration)
MOPITT	Measurements of Pollution in the Troposphere
mpg	Miles per gallon
MSW	Municipal solid waste
MTD	Maximum tolerated dose
NAPAP	National Acid Precipitation Assessment Program (a US program evaluating acidic deposition)
NAS	National Academy of Sciences (US body of scientists formed by a Congressional act)
NASA	National Aeronautics and Space Administration (a US agency)
NICAD	Nickel-cadmium batteries
NIMBY	Not in my backyard
NOAA	National Oceanic and Atmospheric Administration (a US agency)
NOAEL	No observed adverse effect level
NPL	National Priority List (a US list of high-priority hazardous-waste sites)
NRC	National Research Council (an arm of the US NAS)
NTP	National Toxicology Program (a US program evaluating chemical toxicity)
ODP	Ozone-depletion potential
OECD	Organization for Economic Cooperation and Development (organization of 29 prosperous nations)
OTA	Office of Technology Assessment
P^2	Pollution prevention
PBT	Persistent, bioaccumulative, toxic
pCi/l	Picocuries per liter (a unit of concentration for radioactive substances)
PM	Particulate matter
PM_{10}	Particulate matter that is less than 10 μm in diameter

$PM_{2.5}$	Particulate matter that is less than 2.5 μm in diameter
PNGV	Partnership for a New Generation of Vehicles
POP	Persistent organic pollutant
ppb	Parts per billion (a unit of concentration)
ppm	Parts per million (milligrams per liter, a unit of concentration)
ppt	Parts per trillion (a unit of concentration)
PSC	Polar stratospheric cloud
PV	Photovoltaic
RCRA	Resource Conservation and Recovery Act (a US law)
RDF	Refuse-derived fuel
RfD	Reference dose
SDWA	Safe Drinking Water Act (a US law)
SS	Suspended solids
SUV	Sports utility vehicle
TRI	Toxic Release Inventory (US list of chemicals released into environment)
TSCA	Toxic Substances Control Act (a US law)
TUR	Toxics use reduction
UN	United Nations
UNDP	UN Development Program
UNEP	UN Environmental Program
UNICEF	UN International Children's Emergency Fund
USDA	US Department of Agriculture
USGS	US Geological Survey (a US agency)
UV	Ultraviolet
WHO	World Health Organization (a UN agency)
WMH	Waste-management hierarchy
WMO	World Meteorological Organization (a UN agency)
ZEV	Zero-emission vehicle

Chemical abbreviations and formulas

BaP	Benzo[*a*]pyrene (a PAH formed during combustion)
^{14}C	Carbon-14 (a radioactive form of carbon)
CCA	Chromated-copper arsenate (used to protect wood against decay)
CCl_2F_2	Freon-12 (the best-known CFC)
CFC	Chlorofluorocarbon (an ozone-depleting chemical)
CFC-12	Freon (the best-known CFC)
CH_4	Methane (a greenhouse gas)
ClO	Chlorine monoxide (in the stratosphere it promotes ozone depletion)
CO	Carbon monoxide (a toxic chemical formed by incomplete combustion)
CO_2	Carbon dioxide (a greenhouse gas)

DDE	Dichlorodiphenyldichloroethylene (a DDT degradation product)
DDT	Dichlorodiphenyltrichloroethane (a once commonly used insecticide)
DEHP	Di(2-ethylhexyl) phthalate (used in plastic to make it flexible)
DES	Diethylstilbestrol (a potent synthetic estrogen)
Dioxin	2,3,7,8-TCDD (sometimes refers to the whole dioxin family)
DMSO	Dimethyl sulfoxide (chemical promoting transport of chemicals across skin into body)
DNA	Deoxyribonucleic acid (the genetic material)
H^+	Acid hydrogen ion (an ion that makes water acid)
HCFC	Hydrochlorofluorocarbon (a substitute for CFCs)
HCHO	Formaldehyde (a chemical found in many household products, often as a residual)
HCl	Hydrochloric acid (a common acid)
HDPE	High-density polyethylene
HFC	Hydrofluorocarbon (a substitute for CFCs)
^{40}K	Potassium-40 (a radioactive form of potassium)
LDPE	Low-density polyethylene
MIC	Methyl isocyanate (responsible for the massive Bhopal explosion)
MTBE	Methyl tertiary butyl ether (a chemical added to gasoline to provide oxygen)
N	Nitrogen
N_2	Nitrogen (diatomic nitrogen, the form found in the atmosphere)
N_2O	Nitrous oxide (a greenhouse gas, also used as anesthetic, known as “laughing gas”)
NO_2	Nitrogen dioxide (a common air pollutant, which also leads to acid deposition)
NO_x	Nitrogen oxides (common air pollutants that contain nitrogen)
O	Single oxygen atom
O_2	Oxygen (diatomic oxygen, the form found in the atmosphere)
O_3	Ozone (triatomic oxygen, a common air pollutant)
PAH	Polycyclic aromatic hydrocarbon (common pollutants formed during combustion)
PAN	Peroxyacetyl nitrate
PBDE	Polybrominated diphenyl ether (a fire-retardant chemical which is persistent and bioaccumulative)
PCB	Polychlorinated biphenyl (now-banned chemicals once commonly used in electrical equipment to prevent fires)
PERC	Tetrachloroethylene (perchloroethylene, a dry-cleaning solvent)
PET	Polyethylene terephthalate (a common plastic often used to make soft-drink bottles)

PFC	Perfluorocarbon (a greenhouse gas)
PFOS	Perfluorooctane sulfonates (stain repellants and fire-fighting chemicals, environmentally persistent and bioaccumulative)
Po	Polonium (a naturally found radioactive element)
PVC	Polyvinylchloride (a plastic)
Rn	Radon (a naturally occurring radioactive gas)
SF_6	Sulfur hexafluoride (a potent greenhouse gas)
SO_2	Sulfur dioxide (a common air pollutant, which also leads to acid deposition)
TBT	Tributyltin (biocide used to coat maritime ships to prevent growth of fouling organisms)
TCDD	2,3,7,8-tetrachlorodibenzo-*p*-dioxin (most toxic form of dioxin commonly called “dioxin”)
TNT	2,4,6-trinitrotoluene
^{238}U	Uranium-238 (a radioactive isotope of uranium)
VOCs	Volatile organic compounds (or volatile organic chemicals)

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

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[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.

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[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

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[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 (1g 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%

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[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,

Table 1.2 Pollutant types

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

[a] Acids, and 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.

and other chemicals. Other natural chemicals may become pollutants too, but sometimes because man-made conditions allow them to build up to dangerous levels. ■ The radioactive chemical *radon* is produced from the radioactive uranium naturally found in rocks and soil around the world. Only small concentrations of radon are found in outside air. However, radon can seep up and into our constructed buildings from underlying soil and rocks. Inside the building, concentrations build up to levels higher than those outside. Radon is associated with human lung cancer. The US Environmental Protection Agency (EPA) ranks radon second only to environmental tobacco smoke as an environmental health risk. ■ *Arsenic* is also a natural chemical. Until recently it was not a problem to people in Bangladesh and India. However, millions of wells were drilled to provide clean drinking water to Bangladeshis and Indians, freeing them from having to drink badly contaminated surface water. Unfortunately, arsenic in the rock and soil dissolves into the well water. The result is a massive ongoing poisoning event in which millions suffer from arsenic poisoning. ■ Governments regulate human exposure to the carcinogen *asbestos*, which is found in old insulation and tiles. However, asbestos is a natural substance and is found in unexpected places. In El Dorado County, California booming population growth has meant building homes in previously unoccupied regions, including those rich in asbestos deposits. Chronic asbestos exposure has been shown in certain regions of Turkey, where asbestos exposure is naturally high, to lead to respiratory diseases and cancer. It has also been a dangerous workplace pollutant.

Pollutant sources

"I am, therefore I pollute." That applies to any process: ■ Motor vehicles including cars, buses, airplanes, ships, and off-road vehicles. ■ Chemical and petroleum refineries. ■ Manufacturing facilities. ■ Commercial operations such as dry cleaners, bakeries, and garages. ■ Plants that generate electric power by burning coal, oil, or

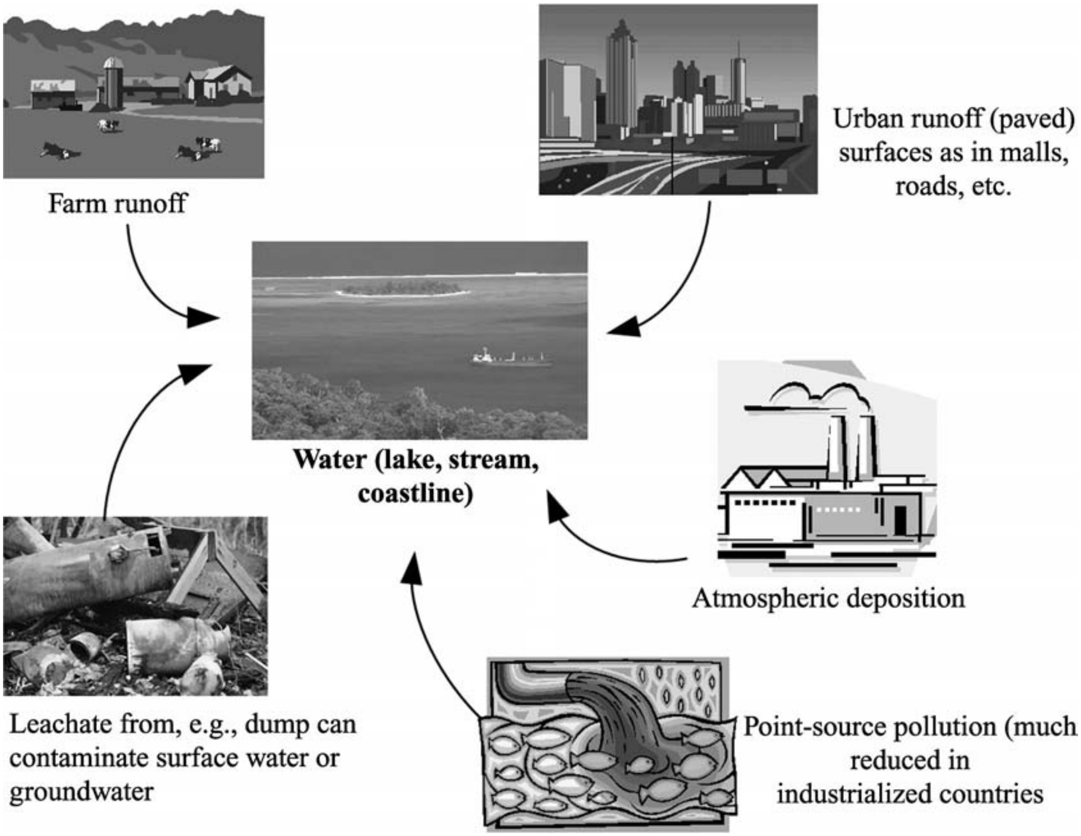

Figure 1.1 Sources of water pollution. Source: US EPA

natural gas. ■ Agricultural operations growing crops or raising animals. ■ Food processing operations. ■ Mining operations. ■ Construction operations. ■ Military operations. ■ Forestry operations. ■ Construction and road building. ■ Consumer product use. ■ Municipal operations including drinking-water and wastewater treatment, and road maintenance. ■ All activities occurring in commercial and municipal buildings, and in private dwellings.

Pollutants reach the environment in many ways as illustrated for a body of water in Figure 1.1. As the population grows, consumption per individual grows. Technologies are becoming larger too. Thus, the scope of all the activities just mentioned grows too. Without concerted effort to prevent it, pollution and other forms of environmental degradation will also grow.

Pollutants move

Although pollutants seldom stay in one place, we often act as if they do. Countries, laws, and environmental agencies often have individual laws for air, water, and solid waste. But pollutants move through air, water, and soil, and may contaminate food as well. Pollutant effects are typically greater near their source, but pollutants often move and may have effects far from their sources too.

Pollution is greatest near the source

Many pollutants are detected far from the point of emission, and can exert adverse effects at a distance – acid deposition is an example. But the greatest effects typically arise near the emission's source. *Dioxins* emitted from an incinerator can also travel thousands of miles. But, again the highest fallout occurs near the incinerator. Dioxins settle onto vegetation, crops, and soil. Cattle and other animals eat the contaminated forage or grain and store absorbed dioxins in their fat. Humans eating fatty meat, such as hamburgers, absorb dioxins into their own bodies and fat.

Some effects occur far from the source

Pollutants often move *transboundary*; that is across national boundaries via air currents, rivers, or, sometimes, with migrating animals such as whales. Damage may occur far from the point of emission. This complicates the ability of a government to reduce pollution within its borders.

Water movement

Chemicals spilled into a river in one country flow downstream into other countries: ■ In the year 2000 a Romanian mining operation spilled cyanide and hazardous metals into a Romanian river which flowed into the Tisza River and later the Danube. The Associated Press reported that one Yugoslav mayor stated that 80% of the fish in the Tisza near his town died. Another mayor said "The Tisza is a dead river. All life in it, from algae to trout, has been destroyed." ■ In a different accident at a Swiss facility, large quantities of chemicals washed into the Rhine River, which carried them into France and Germany killing fish and other aquatic life along the way.

Air movement

Sulfur dioxide and nitrogen oxides emitted to the atmosphere from sources burning fossil fuels can be blown many hundreds of miles. Converted to acidic substances as they travel, the result is acid deposition settling onto water and land over a whole region. Acid builds up over time in soil and water bodies as emissions continue. Forests and lakes in Sweden are harmed by acid originating in the European countries to its south. Japan's environment is damaged by coal burning in China. ■ The "grasshopper effect" is a special case of pollutant movement. The insecticide *dichlorodiphenyltrichloroethane* (DDT) illustrates the grasshopper effect. When DDT is used in a Latin American country, it evaporates and the wind blows it north. When it reaches cooler air, allowing it to condense, it comes to Earth. On a warm day, it evaporates again. The process repeats itself, sometimes many times. Once it reaches the far North, it is too cold for DDT to evaporate again. The Arctic is a *sink* for DDT and other similar *persistent organic pollutants* (POPs). Moreover, DDT and other POPs enter the Arctic food chain and build up in the fat of marine mammals. Inuit, the Arctic's indigenous people, eat the contaminated mammals and DDT builds up in their body fat to levels among the highest seen in the world. Canada actively works for international treaties to cut pollutant flow from the south into the Canadian north.

Sometimes, airborne pollutant movements are so prominent as to lead to *global change* such as stratospheric-ozone depletion, or global climate change. Even acid deposition, a regional phenomenon, is so widespread as to be global. At least one water pollutant, "fixed" nitrogen,[2] is also having such widespread regional effects as to be global. You will observe more "moving" pollutants throughout this text.

Box 1.4 | Pollutants can be buried in sediments

Sediments are materials deposited at the bottom of a lake, river, or other water body. They mostly contain materials carried to the water in rain or snow runoff from surrounding land. Sediment is composed of soil, minerals, and organic material. Once in the water the material settles to the bottom as sediment. Very find particles may remain suspended for quite some time rather than settling out; such suspended solids can be very damaging to aquatic life. By its very nature, sediment is buried by additional incoming sedimentary material. Pollutants such as metals or long-lived organic chemicals may be buried in sediments, but cannot be depended upon to remain buried. Bottom-feeding organisms may take the pollutants back up, and reintroduce them into the food chain. Riverine and coastal-area sediments are sometimes dredged, which also brings contaminants back to the surface. Natural water currents such as a strong river flow also move sediment, especially that near the surface. This is another illustration of the fact that pollutants, even after settling in one place often don't stay put.

Pollutants also change form

Organic substances

In a very cold locale such as the Arctic, pollutants may persist indefinitely. Fortunately, in more moderate climes, pollutants are modified. In many, but not all, cases modifying the pollutant also lessens the risk associated with it.

Microbial degradation is vital

Organic materials, including plant debris and animal remains, serve as food to many microorganisms such as bacteria and fungi. Degrading waste is a major *natural service* that microorganisms provide to the environment; otherwise debris and wastes would build up to intolerable levels. ■ Carbon dioxide and water are end products of metabolism. An organic substance degraded all the way to these two substances is said to be *mineralized*.[5] One caution. Some microorganisms do not require oxygen to degrade organic substances. In these cases, carbon dioxide is not an end product of degradation. Instead, a common end product is methane, "swamp gas," arising from mud where it is produced by bacteria living without oxygen.

Physical factors contribute

Physical factors help to break down organic substances, including synthetic organic substances. ■ Even in the absence of microorganisms, *atmospheric oxygen* helps to degrade organic substances especially at warm temperatures and in sunlight. ■ *Heat* is important, the higher the temperature, the more rapidly organic materials break down. ■ Summer *sunlight*, especially its ultraviolet radiation, assists in degrading organic materials. ■ *Wave motion* in water brings pollutants to the surface, exposing them to sunlight, heat, and oxygen. This also assists in degradation.

When natural systems are not enough

There are cases, often situations for which humans are responsible, when natural systems are overwhelmed. Food-processors, tanneries, and paper mills are among the facilities that, especially in the past, released large quantities of organic pollutants to rivers, severely degrading water quality. ■ Another reason for slow degradation will be seen in Chapter 14: certain synthetic organic chemicals have structures that make it very difficult for microorganisms and other living creatures to degrade them. This is true of many *polychlorinated* chemicals dioxins such as DDT, and polychlorinated biphenyls (PCBs). These persistent pollutants may remain for many years in the environment and in animal tissues and, in very cold climates, may persist indefinitely.

Inorganic pollutants

Inorganic chemicals are not converted into carbon dioxide and water – they are already mineral substances. Inorganic substances undergo chemical changes, but are not destroyed in the same manner as organic materials. Think about a metal. It undergoes chemical changes, but is not destroyed. Box 1.2 shows metals burned to metal oxides. However, oxidation can occur without burning as when the

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[5] Mineralization can involve many reactions and, depending on conditions, a long period of time. Mineralized substances are *oxidized*; that is, oxygen has become part of their structure. Although many organic chemicals, such as sugars, already contain oxygen, oxygen is still involved in their degradation. Organic substances such as hydrocarbons do not contain oxygen, but oxygen is incorporated as they are mineralized to carbon dioxide and water. Go back to Box 1.2 and notice that oxygen is also added during combustion; that is, these substances too are oxidized. This is a similarity between how fire and living creatures transform substances. However, oxidation carried out by living creatures is the very process of life, and is much more elaborate and controlled than is the case with fire.

iron in a bridge reacts with oxygen in the air, and is oxidized to the reddish iron oxide. However, if you take a sample of iron oxide, and heat it, you can recover the iron. The oxygen can also be recovered if you prevent it from escaping into the air. Also in Box 1.2 you see that sulfur reacts with oxygen to yield sulfur dioxide. Again, under proper circumstances, both the sulfur and oxygen can be recovered. To review the difference between organic and inorganic chemicals, see Box 1.3.

Questions 1.3

1. What characteristic of inorganic acids allows them to build up in water and soil over time?
2. Why do organic pollutants typically degrade more slowly in groundwater than in surface water?
3. (a) How are physical conditions in sediment different to those in surface water? (b) How does this affect the degradation of organic pollutants?
4. Sediment contains *anaerobic* microorganisms (microbes that do not, or cannot, use oxygen). Anaerobic microbes often produce methane as an end product. How might the methane be mineralized?

Pollution extremes

Pollution that devastates

Sometimes an event is so devastating that it changes our way of looking at the world. The deadly explosion occurring in Bhopal, India is one such event. Union Carbide, an American-owned factory in Bhopal, manufactured the pesticides Temik and Sevin. In the process it used *methyl isocyanate* (MIC), an extremely toxic volatile liquid that reacts violently with water. However, the factory lacked stringent measures to exclude water from contact with MIC. On the night of December 2, 1984, as Bhopal's people slept, water entered a storage tank containing 50 000 gallons (189 000 l) of MIC. The Indian government later said that improper washing of the lines going into the tank caused the catastrophe. Union Carbide claimed that a disgruntled employee deliberately introduced water. Whatever the cause, the resulting explosion released 40 tons (36 tonnes) of MIC and other chemicals over the city. Up to 2500 residents of Bhopal were killed overnight, and about 8000 died in the following 3 days. Another 120 000 to 150 000 remain chronically ill, as of 2003, with respiratory infections and neurological damage. The catastrophe was worsened because many people lived crowded close around the factory (Figure 1.2) and because poisoned residents received little medical attention at the time of the accident. Compensation for people's injuries even in small amounts was also long in coming. In 1984, Union Carbide had almost 100 000 employees. After Bhopal it almost went out of business and by 1994 only employed 13 000. As of 2003,

Figure 1.2 Bhopal shanties adjacent to Union Carbide plant (towers seen at upper right in 1985). Photo by Wil Lepkowski. Permission: *Chemical & Engineering News*, American Chemical Society

a Bhopal court still has criminal charges pending against the person who was Chief Executive Officer of Union Carbide at the time, accusing him of having consciously decided to cut back on safety and alarm systems at the plant as a cost-cutting measure. In 2001, Dow Chemical purchased what was left of Union Carbide.

Pollution that is less obvious

Whereas Bhopal represents horrendous pollution, its opposite can present a quandary – how risky are barely detectable amounts of pollutants in the environment? Modern analytical chemistry can detect industrial chemicals almost anywhere: soil, water, air, food, and in the bodies of people, animals, and plants. When chemical levels are high or obviously causing harm, we agree that something must be done. But think about a hypothetical lake in which 20 different synthetic chemicals have been detected. Each is present in a tiny amount very unlikely to cause a problem, certainly not in the short term. Should we concern ourselves with these?

Some possibilities could increase your concern.

- Some of the 20 contaminating chemicals are very similar to one another. Similar chemicals may have the same mechanism of action, that is, each may exert toxic effects in similar ways. The levels of each added together could pose a potential problem. Organophosphate pesticides are a case in point. There are many different organophosphates, but each acts in a similar way. So, if several lake contaminants are organophosphates, the total concentrations added together may be cause for concern.
- Even if none of the chemicals act in the same way in the body, the possibility exists that some combination of them may exert a *synergistic* effect, that is, one chemical could magnify the effect of another out of all proportion to its concentration. It is difficult to

test for synergistic effects in the laboratory because, even if there were only a few rather than 20 chemicals, we could not test them in all possible combinations. Even testing a few simple mixtures is complicated and expensive. However, it is possible to examine the effect of the contaminated water itself (not its individual components) on wildlife species.

- Species differ widely in their sensitivity to toxicants. One species may be thousands of times more sensitive than another. Within individual species, including humans, there is also a range of sensitivity.

Other possibilities could decrease your concern.

- Some chemicals *inhibit* the toxicity of other chemicals, lessening the chance of an adverse effect; that is, they act as antidotes.
- There are hundreds or thousands of *natural* chemicals in the water too, and many may be chemically similar to the synthetic contaminants.
- An animal or human body has no way of knowing whether a chemical is natural or synthetic – it deals with contaminants using biochemical pathways that have evolved over millions of years.
- Twenty or thirty years ago you would have been unable to even detect most of these contaminants – it is only now with sophisticated analytical methods that they can even pose a concern.

Questions 1.4

1. Both of the following two statements refer to the hypothetical contaminated lake described above. (a) It is alarming that no pristine places are left on Earth, and even more alarming that chemicals are detected in our bodies. Our health, our children's health, and the environment may be affected. Let's force companies to adopt the *precautionary principle*, that is, to demonstrate that a new chemical is safe before it can be sold or allowed into the environment. And let's make sure that chemicals already on the market are tested too. (b) We cannot worry about every low-level contaminant. It would be prohibitively expensive or impossible to reduce emissions to zero or (if the chemical occurs naturally) to reduce it to natural background levels. Nature adjusts well to small levels of most chemicals. We should devote our resources to higher-risk problems. Taking the chemical off the market could introduce other problems. Or it may be replaced by another chemical that, although it seems fine now, may also be found to pose problems in the future. Which of these two statements do you most tend to agree with and why?
2. Consider a different situation, one occurring more frequently as people move into areas previously devoted to farming. New residents may complain about farm odors when farmers spread sewage sludge as a fertilizer or to improve soil quality. Both state and federal Environmental Protection agencies support the spreading of carefully treated sludge. However, new residents complain. One said, "The human body knows when something is not good for you. Sludge

must be bad. It smells so bad, it can make you nauseous." Put yourself in the position of these residents. (a) Does the fact that it smells badly mean that airborne substances are present at a harmful level? Explain. (b) Before you decide whether concerns are legitimate, what questions do you want to have answered? (c) Another complaint of nearby residents was, "When someone spreads sludge, you get flies in your house and on your house. It's awful." Do flies present a potential danger? Explain. (d) When people are thinking about buying homes in a rural area, what questions should they ask? (e) Should sellers be required to give potential buyers information on sludge spreading or similar operations around their possible homes? (f) What would your reaction be if a large industrial farm (one with thousands of pigs or cattle) moved into the neighborhood *after* you had already settled there? Would you be concerned? Explain.

SECTION III

Global pollution and global environmental health

At the Earth Summit held in Rio de Janeiro, Brazil in 1992, the heads of 120 governments met together. Their mission was to decide how to deal with the Earth's environmental problems, including climate change, air pollution, deforestation, and loss of biodiversity (extinction of species). Agenda 21 came from the 1992 summit, a strategy for sustainable development or, as one participant phrased it, "a blueprint for how humankind must operate in order to avoid environmental devastation." Five years later in 1997, 158 governments gathered for an Earth Summit +5 to discuss progress. Unfortunately, they agreed that the world environment continued to deteriorate – greenhouse gases continue to accumulate, air pollution in cities is worse, fresh water is more contaminated, biodiversity continues to decline, and deforestation continues – an area of tropical forest the size of Iowa disappears each year. A saddened Malaysian delegate exclaimed, "Five years from Rio we face a major recession – not economic, but a recession in spirit. We continue to consume resources, pollute, and spread and entrench poverty as though we are the last generation on Earth."

Pollution in less-developed countries

Environmental degradation in less-developed countries (impoverished countries, also often referred to as "third-world" countries) is "pervasive, accelerating, and unabated" according to the Asia Development Bank (see issues in Table 2.1). In an *Atlantic Monthly* article,[6] author William Langewiesche describes one third-world city, New Delhi, India: ". . . the pollution . . . seemed apocalyptic. The streams

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[6] Langewiesche, W. and Halweil, B. The Shipbreakers. *Atlantic Monthly*, **286**(2), August, 2000, 33–49.

were dead channels trickling with sewage and bright chemicals, and the air on the street barely breathable." Rivers in some impoverished cities are described as "open stinking sewers." The impact of such conditions on humans is sobering. ■ The World Health Organization reports[7] that in 1995 at least 3 million people, mostly impoverished children, died from drinking water contaminated with untreated human waste containing infectious microorganisms or parasites. Having too little drinking water also contributes to these deaths. Almost half the world's population suffers from waterborne diseases. ■ Millions of additional deaths arise from infections resulting from eating contaminated food, and from unsanitary living conditions. ■ Just by breathing the air, children in a heavily polluted third-world city such as New Delhi inhale the equivalent of two packs of cigarettes each day. But living in a rural area may not help – of 2.7 million deaths each year that result from air pollution, 2 million arise from indoor air pollution in rural areas. Intolerable indoor air pollution occurs because almost 90% of third-world households burn straw, wood, or dried manure inside their homes for cooking and often for heating, with very poor ventilation.

Gross pollution immediately endangers people, but the damage goes further. Air pollution affects the growth of natural vegetation and of human crops. Regardless of this dreary description, the Asia Development Bank expressed the belief that Asia, "still has the opportunity to follow a different economic–environmental pathway, one that builds a clean urban–industrial economy from the bottom up, and avoids much of the costly, inefficient, and embattled institutional and technological experience of industrialized countries."

Box 1.5 | "A letter from India."

Vapi is an industrial city in Gujarat, India. Author Jean-François Tremblay[8] heard a former resident of this city describe ponds that looked like jelly, and brightly colored streams flowing from dye-making factories. Tremblay was intrigued by these stories and decided to visit Vapi, which along with other industrial areas in Gujarat was named by Greenpeace (an environmental organization) as among the world's most toxic "hot spots."

Tremblay found that the pollution was due to the manufacture of dyes, fine chemicals, pharmaceuticals, and pesticides. Facilities flagrantly pollute, presumably to keep production costs low. He wrote: "most of the plants are repugnant, spewing thick smoke and typically surrounded by dirty water. During my hours in a rickshaw touring the city, I see little evidence of attempts by industry to give something back to the town. The sides of the road are littered with garbage, which apparently is never picked up." He found it: "perplexing . . . how little effort local companies

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[7] World Health Organization. *Bridging the Gaps*. The World Health Report 1995. Geneva: World Health Organization, 1995.

[8] Tremblay, J.-F. Letter from India. *Chemical and Engineering News*, **78**(20), May, 2000, 27–28.

put into trying to look even a little less repulsive." He described a stream with people living along it in shacks in the midst of pollution. Its squalor and poverty reminded him of a Charles Dickens novel. But, unlike nineteenth-century England, Vapi factories have guards who tried to prevent Tremblay from taking photographs. The obviously old factories suggested to Tremblay that the manufacturers were using old and inefficient processes, more likely to cause industrial accidents. When he asks his rickshaw driver about accidents, the man takes him to a factory that had blown up 2 years earlier, and then drove him to another that had closed because of a fire.

Finally Tremblay finds a clean modern facility, one with a wastewater-treatment plant. Here a guide assures him that all emissions from Vapi factories "meet standards" and "pollution is very minor." Later a long-term Vapi resident says pollution is lessening. His family now dares to go outside their home and breathe the air again, and the leaves on a tree in his front yard are turning green again. In the year that Tremblay visited, an Indian publication reported that an inquiry into conditions in the Vapi area, "found evidence of reckless discharge of industrial effluents and disposal of hazardous wastes."

Poverty and the environment

The UN Environmental Program's Helmsman Töpfer has said, "To fight poverty is also to fight environmental problems in the world." Indeed poverty is often associated with gross pollution and poor environmental health. It need not be that way. Good governance – a caring government that is not corrupt – can accomplish much, even with few resources. An example is Curitiba, Brazil, described as a first-world city in a third-world country. A less dramatic example is the Indian state of Kerala where people with very low incomes have better environmental health than many in more well-to-do Indian states. On the other hand, pollution still occurs in wealthy countries. In the US cities of Houston and Los Angeles, air pollution levels are above health-based standards. Moreover, consider food contamination. The US Center for Disease Control and Prevention says that millions of Americans each year suffer diarrhea thought to be due to contamination of foods by infectious organisms. Serious outbreaks of waterborne diseases have also occurred in recent years. As discussed in Chapter 10, unless ongoing vigilance is maintained, and water- and wastewater-treatment systems are carefully maintained, communities can regress to conditions of an earlier era.

SECTION IV

Root causes

"If current predictions of population growth prove accurate and patterns of human activity on the planet remain unchanged, science and technology may not be able to prevent either irreversible degradation of the environment or continued poverty for much of the world." Such was one sentence in the first-ever joint statement of the US National Academy of Sciences and its British equivalent, the Royal Society of London, in 1992. One member commented, "Scientists . . . are doing a lot more talking about global warming and ozone depletion than they are about the basic forces that are driving those things." The equation I = PAT is sometimes used to describe the environmental impact of humans:

Impact = Population × Affluence × Technology

The Earth's increasing population has the greatest impact in areas where population is increasing the fastest. High levels of consumption occur disproportionately in rich countries. The technology of greatest concern is large-scale technology, which has the greatest impact.

Population

Most population growth is occurring in impoverished countries, especially in their "explosively growing" cities. By 2005 more than 3 billion people, half the world's population, will live in cities, according to the UN Population Division. By 2025 the world may have 650 cities each with a population greater than 1 million. By 2015, 23 "megacities" (cities with populations of 10 million or more) are expected, all but 4 in third-world countries. Four cities, Bombay, Dhaka, Lagos, and São Paulo, are each expected to have over 20 million people. Much of this dramatic growth is due to in-migration from impoverished rural areas. Cities are growing much faster than a country's overall population. The average age of people in cities is very young. As Harvard biologist Edward Wilson phrased it: "The people of the developing countries are . . . far younger than those in the industrial countries . . . The streets of Lagos, Manaus, Karachi, and other cities in the developing world, are a sea of children. To an observer fresh from Europe or North America, the crowds give the feel of a gigantic school just let out."

Think about the waste produced by a huge city, even one in a very poor country. In Manila, a city of 10 million, just one garbage dump, Payatas, receives 3000 tons (2730 tonnes) of garbage a day. Most poor cities cannot pick up all the trash. Streets are littered with paper, plastic, bottles, and scraps of all kinds. Although only a small percentage of third-world residents own motor vehicles, the pollution from these vehicles is often uncontrolled and fouls the city air. So does the common practice of open burning. Worldwide, about 2 billion people lack basic sanitation. City residents may lack even simple sanitary latrines, let alone flush toilets. Because most sewage remains untreated, water supplies are polluted. Many people lack clean drinking water, or lack even enough drinking water. Beyond the major effects on their own peoples' health, large cities have impacts far beyond their borders: "Modern high-density settlements now appropriate the ecological output and life-support functions of distant regions through trade

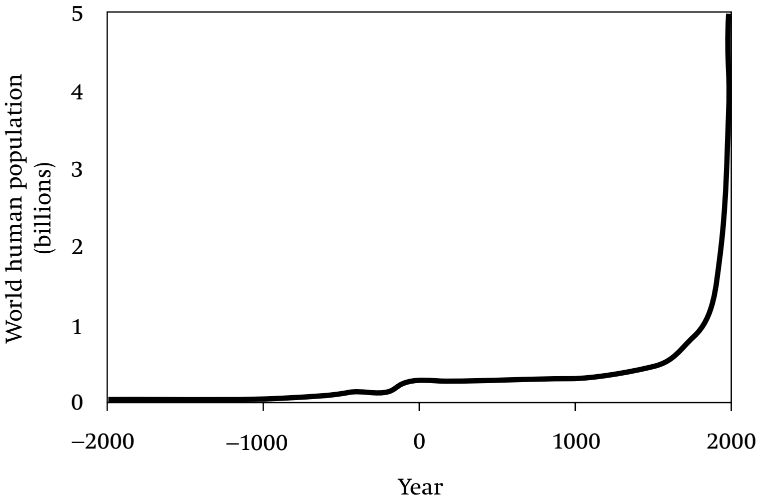

Figure 1.3 World population growth. Source: UN Population Program

and commerce, the generation and disposal of wastes, and the alteration of nature's cycles. As cities continue to attract more people and produce and consume more, they become "black holes" that soak up the ecological output of entire regions," this according to a Johns Hopkins University report.[9]

World population growth is illustrated in Figure 1.3. However, diseases – AIDS most prominently – are expected to lower the population of some countries, especially in sub-Saharan Africa. If AIDS continues to spread, population may fall in other countries as well. Drug-resistant tuberculosis is also rapidly increasing. In Western Europe, population has stabilized, but the US population is increasing rapidly especially through immigration. At current growth rates, the US population may double within 60 years. It is difficult for a nation of immigrants such as the United States to consider curbing immigration. However, a growing population has an adverse environmental impact whether the growth is due to increasing births within a country or ongoing immigration.

Questions 1.5

Some students in prosperous societies, upon learning that AIDS may reduce population in badly affected countries say the following: AIDS deaths are sad, but if they decrease population maybe that is good. Aside from the moral implications of this reaction, consider other factors. One is that history tells us that a population reduced by disease, such as Europe's medieval plagues, quickly rebounds. Another is that AIDS is unlike other infectious diseases, which usually infect all portions of the population. Those dying of AIDS are the sexually active population – primarily young adults, including farmers, teachers and health-care workers. Sub-Saharan

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[9] Hinrichsen, D., Blackburn, R., and Robey, B. Cities will determine living standards for mankind. *Population Reports* (Special Istanbul+5 edition), June, 2001.

Africa already has about 10 million orphans, a number expected to quadruple in the coming years (see Brown and Halweil in Further reading).

1. What is the likely stability of countries with large numbers of uncared-for orphans, countries that are also losing the most productive portion of their population? Explain.
2. How could this lack of stability affect a country's environment?
3. How could conditions in these unstable countries affect wealthy countries?

Affluence and consumption

"Since 1950 we have consumed as many goods and services as has all previous humanity in the past 10 000 years." Even if population growth ceased today, many believe that a world with more than 6 billion people (the current population) is not environmentally sustainable – not without major changes. Rich countries sometimes blame environmental degradation on huge populations in poor countries. Poor countries resent this, and blame high levels of consumption in wealthy societies for environmental degradation and resource depletion. Indeed, rich individuals consume a great deal more per person than do their third-world counterparts. The United States, with less than 5% of the world's people, uses 25% of the Earth's material and energy resources. The richest 20% of the world's population own 87% of the world's motor vehicles, use 84% of all paper and 57% of the energy. Rich individuals are also more likely to affect environments distant from where they live, as they buy more products produced elsewhere in locales with poor environmental protection. Citizens of wealthy countries are only slowly beginning to confront these issues.

Technology

Large-scale technologies sometimes devastate an environment. A case in point is "mountain-top removal" described by one reporter as "mountain-range removal" that leaves "flat moon-like expanses of land." Coal-mining companies in the US states of West Virginia and Kentucky blast away as much as 700 ft (213 m) from mountain tops, to reach coal seams. Then 20-story-high machines, "draglines", move in to shovel away the material at 130 tons (118 tonnes) a bite. Over recent decades, hundreds of millions of tons have been dumped into adjacent valleys burying at least 900 miles (1450 km) of streams. One stream, the Little Coal River, once supported barge traffic. Now parts are so congested that not even canoes can pass. Companies claim it is too expensive to handle the waste in any other way. The noise, dust, and truck traffic, and sometimes flying rocks, lead to the demise of nearby communities as people continue to move away. A 1977 federal law specifically forbids extracting coal in this way, but influential mining companies continue to evade enforcement. The law also requires that a mountain's contour be restored after coal mining. This too gets poor compliance. Another result of mountain-top removal is slurries stored in about 600 pits that contain mining spoil, coal dust, water, and metals. In the year 2000, a Kentucky pit burst spilling about 250 million gallons (946 million liters) into the Ohio River watershed "burying or poisoning 90 miles (145 km) of stream; polluting public water supplies; clogging water-treatment plants; shutting down schools, restaurants, laundries, and power generation; and wiping out fish, snakes, turtles, frogs, salamanders, mussels, and other aquatic fauna."

To give you an idea of how much waste mining produces, look at Worldwatch Institute figures.[10] ■ Only 2.5% of the lead ore mined in the United States is lead; the other 97.5% is waste. ■ Gold is much worse: of the 7235 million tons gold ore mined, 0.000 33% is gold. The other 99.999 67% is waste. Gold ore produces so much waste because of its high value. Low-percentage ores that would not be worth mining for most metals are, for gold, worth the cost. Although mining of coal or mineral ores is one of the world's major polluting industries, it is not alone. Modifying technology to lessen environmental damage is a major challenge. Indeed, lower environmental impact is necessary if the poor of the world are to attain better living standards. Approaches used to lessen the impact of population growth, consumption, and technology will be discussed in later chapters.

SECTION V

Our actions have consequences

Each of us impacts upon the environment. Consider a car. We indirectly impact upon the environment when we buy a car because of the impact of recovering the resources to make the car and of manufacturing the car. It produces pollution and other environmental impacts to use and maintain. And it has impacts when disposed of or recycled. When we buy a product, we accept the impact caused by producing it. However, for a specific product, we typically don't know the environmental impact of recovering the resources that go into it, or the impact of manufacturing it. If it's a food product, we often don't know the conditions under which it was grown or processed. Lastly, we often don't even know what will happen to it once it is disposed of. Think about several agricultural products. ■ Affluent individuals who buy flowers in winter may be unaware that the less-developed countries producing them use more dangerous pesticides or larger quantities of pesticides than used in developed countries, that the pesticides often pollute surface or groundwater, and that workers may be heavily exposed to them. ■ Coffee drinkers in rich

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[10] Sampat, P. Scrapping mining dependence, in *State of the World 2003*, Chapter 6. Washington, DC: Worldwatch Institute, 2003.

countries typically don't know that they drink "sun coffee." Full sun enhances bean yields. However, because "sun plantations" lack the tree canopy of shade farms, fewer insect-eating birds and spiders find shelter among them. What is the result? More pesticides must be used to destroy insects. And without a tree canopy, less tree litter is produced so more synthetic fertilizer is needed. ■ North Americans eat shrimp, most of which is imported. Diners don't see the pollution or environmental degradation produced by third-world shrimp farms. ■ Even when an agricultural product comes from within a wealthy country, the buyer often doesn't know how it is produced. Think about the waste produced by the animals we eat. The US Senate sponsored a study indicating that the United States produces 130 times as much animal waste each year as human waste. But there are no sewage-treatment plants for animal waste. Instead a facility housing thousands of pigs stores their urine and feces in open-air lagoons, and later sprays it onto fields. When amounts sprayed are greater than the soil can absorb, rain can carry pollutants from it into nearby water.

We can evaluate the full impact of a product, including an agricultural product, by using a technique called life-cycle assessment (LCA). This involves evaluating the environmental impact of a product at each stage of its life: (1) When recovering and processing the resources used to make it. (2) During manufacture. (3) During its use and maintenance. (4) During recycling, reuse, or disposal. More information will be given on LCA later.

The "tyranny of small decisions"

There are many ways in which individuals impact upon their environment. "One of the more intimate ways . . . is by taking a pill or washing their hair." Some components of medicines leave the body in urine and feces and enter the sewage system. Also going down the drain are shampoos, cosmetics, toiletry products, and household chemicals. Because wastewater-treatment plants do not remove them all, some enter rivers, sediment, and groundwater. Many pharmaceuticals including antibiotics can be detected in rivers. Some are even detected in drinking water, although at very low levels. Wildlife has the highest exposure to these substances from our toilets, laundry rooms, and kitchens, especially fish and other aquatic life living directly below the effluent pipes of municipal and other wastewater-treatment plants. Although these substances are present in low concentrations, they present real concerns, especially antibiotics. Exposing wildlife and bacteria in water even to low levels of antibiotics can promote the development of resistance. Resistance is a phenomenon in which bacteria develop means to "fight back," to fend off the antibiotics used to treat humans and animal disease. And, "intimate wastes" such as birth-control hormones can exert hormonal action on wildlife even at very low levels.

Box 1.6 | Our actions have impact

■ "More and more we are realizing that a large part of remaining environmental problems comes from the cumulative impacts of our individual actions. These impacts are far more subtle and . . . harder to manage than the single smokestack or wastewater discharge." (Martha Kirkpatrick, Maine Department of Environmental Protection.) ■ "More than half the nation's water pollution problems spring from everyday actions." (National Geographic Society and the Conservation Fund report.) ■ "We know that further progress on many fronts, notably air and water quality, means getting a handle on diffuse sources of pollution that result from millions of people making countless individual choices." (William Reilly, former US EPA administrator.)

Questions 1.6

1. Conservationist Wendell Berry[11] writes, "One of the primary results – and one of the primary needs – of industrialism is the separation of people and places and products from their histories." From an environmental perspective, how does knowing the origin of consumer products or agricultural goods matter? Provide an example.
2. Consider: "The more the population grows, the more the rights of the common will impinge on the rights of the individual." How do you interpret this statement? Provide an example.
3. Choose any product. Answer the following questions about it to the best of your knowledge. (a) Where was it produced? What are the environmental impacts of (b) recovering the resources needed to make it, (c) manufacturing it, (d) using it? (e) What will happen to the product at the end of its useful life?
4. In the United States, the business community spends more money on advertising than on environmental control. Many believe advertising fuels a "culture of waste" that leads to heavy use of energy and other resources. People with money are enticed to buy unneeded products – more clothes, another car or TV, a new product to replace one that is still working well, and frequently second homes. Think about your understanding of the word sustainability. Is consumerism compatible with sustainability? Explain.
5. What are three possible ways that society could control the release of the "intimate" wastes described in this chapter, or reduce their impacts?
6. (a) What are five small decisions that you as an individual make that impacts upon the environment? (b) How might you make each decision differently if you took potential environmental impact into account?

Environmental agencies in developed countries regulate an ever-increasing number of chemicals from an increasing number of sources. But can government regulate every chemical and every source of emissions? Again, think of motor vehicles. Although these

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[11] Berry, W. Back to the land, in *The Best American Science and Nature Writing*, ed. D. Quammen. Boston: Houghton Miflin Co., 2000.

are a major source of air pollution, many people resist testing emissions from their vehicles, or do so resentfully. Could federal, state, and local environmental agencies realistically monitor every small business operation, every home, and every vehicle in the nation? What are other ways to deal with pollution and environmental degradation, and how do we get individuals to buy into these approaches?

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Chapter 2

Reducing pollution

"We aren't passengers on Spaceship Earth; we're the crew. We aren't residents of this planet; we're citizens. The difference in both cases is responsibility."

Astronaut Rusty Schweikart

Some pollution problems are daunting. Thus, even before discussing them, this chapter introduces ways to control – better still, not produce – pollution. This chapter also introduces tools that we can use for assistance in moving toward sustainable societies. **Section I** considers the risks of individual chemicals (to be covered in more detail in Chapter 4). It also introduces comparative risk assessment, which allows us to compare not just the risk of individual chemicals, but the seriousness of various environmental problems: Which pose the greatest risks? **Section II** addresses how a society can protect its environment. Legislation plays a major role. But, many laws stress trapping pollution once it is produced. A newer paradigm is pollution prevention (P^2) or source reduction – changing the process to generate less pollution to begin with. If P^2 is not feasible, reuse or recycle are often good options. P^2 has limitations too, so **Section III** introduces industrial ecology (IE), which looks for ways to mesh human activities, industrial and otherwise, into the natural environment. The tools of IE include life-cycle assessment and design for the environment.

SECTION I

Risk assessment

A question that has confronted us for many years is how to evaluate environmental threats. To respond to this question, the tool of risk assessment was developed over a period of decades. Chemical risk assessment is used to evaluate the risk of individual chemicals one by one. Or, when a number of pollutants or environmental problems must be compared and rated, comparative risk assessment is used.

Chemical risk assessment

Questions 1.4 asked you to reflect on how to decide when pollutants pose an unacceptable risk, but gave you no method to do so. Nonetheless, you probably came to realize that a risk acceptable to one person is unacceptable to another. This chapter introduces a tool, *chemical risk assessment*, which is used to evaluate the risk of individual chemicals. In the United States, members of the National Academy of Sciences have struggled to make this tool more useful, as have several other federal and state agencies including the US EPA and the Agency for Toxic Substances Disease Registry. Risk assessment raises questions that science alone cannot answer, and no one is fully satisfied with the process. However, applied consistently, chemical risk assessment is – within its known limitations – trusted. One of the many instances in which chemical risk assessment is used is in the evaluation of hazardous-waste sites.[1] Just having hazardous chemicals present does not mean that a site is dangerous. Of greater importance is the question: Are humans exposed to these chemicals? If so, in what amounts and how are they exposed – through air, water, food?

Red-flag chemicals

Over the years, investigation has shown that some chemicals have characteristics that warn us of a likely problem. ■ Is the chemical *persistent* in the environment and within living creatures? Persistent chemicals include metals, which cannot be broken down. But some organic chemicals are persistent too, in particular those that microbes or animals have difficulty in degrading, such as dioxins or DDT. ■ Does the chemical *bioaccumulate*, i.e., build up in plants and animals to concentrations higher than found in the environment? Again, dioxins and DDT are examples. ■ Is the chemical very *toxic*? If a chemical has these characteristics, it is referred to as a *persistent, bioaccumulative, toxic* (PBT). Even a low level of a chemical characterized as a PBT warns us to treat it respectfully. Chapter 14 will address organic chemicals that are PBTs and Chapter 15 covers metals that are PBTs.

Comparative risk assessment

Comparative risk assessment can be used in a relatively simple way to compare the risk of one chemical to that of another chemical, as when comparing benzene to lead. However, comparative risk assessment can take us far beyond the risks of individual chemicals. We can use it to compare the risks of various environmental problems with the aim of distinguishing high-priority risks from medium- and low-priority risks. The environmental risks compared may include complicated issues such as acid deposition and stratospheric-ozone depletion – see column 1 of Table 2.1. Comparative risk assessment

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[1] The US EPA uses an exhaustive procedure to analyze a site as to whether it poses a high-enough risk to place on the National Priority List (NPL). NPL sites receive federal attention whereas individual states are left to clean up less-risky sites.

Table 2.1 Results of comparative risk assessment studies. Results of three separate studies are summarized below

1. United States 1990s[a]

Pollution and non-pollution environmental risks

High risk

Habitat alteration and destruction
Species extinction and loss of biodiversity
Stratospheric-ozone depletion
Global climate change

Medium risk

Herbicides and pesticides
Acid deposition
Airborne toxics
Toxics and nutrients, biochemical oxygen demand, and turbidity in surface waters

Low risk

Oil spills
Groundwater pollution
Radioactive chemicals
Acid runoff to surface waters
Thermal pollution

High-risk threats to human health

Drinking-water pollution
Ground-level air pollution
Worker exposure to chemicals (industry/agriculture)
Indoor air pollution

2. Worldwide 2000[b]

Pollution and non-pollution environmental risks – all risks below were deemed high risk

Pollution

Freshwater pollution and scarcity
Air pollution (especially ozone, fine particles)
Global warming
Acid deposition
Municipal-solid-waste generation
Hazardous-waste generation
Increasing energy use
Insufficient knowledge of chemicals in use
New threats: nitrogen-fertilizer and heavy-metal pollution

Other environmental threats

Human population growth
Land degradation (undermines agriculture)
Deforestation and forest quality loss
Marine fisheries over-fished
Habitat loss for wildlife
Extinction of plant and animal species
Loss of biodiversity

3. High-risk threats to human health[c]

Drinking-water pollution
Heavy air pollution, outdoors and indoors
Untreated human waste and lack of basic sanitation (with resulting exposure to pathogenic microorganisms)

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[a] As determined by the Science Advisory Panel of the US Environmental Protection Agency. US EPA *Reducing Risk: Setting Priorities and Strategies for Environmental Protection. The Report of the Science Advisory Board to W. K. Reilly, Administrator*, SAB-EC-90-021. September, 1990.

[b] Compiled from: United Nations Environmental Program (UNEP) report, Global Environment Outlook 2000 (http://www.grida.no/geo2000/), and the OECD (see below) Environmental Outlook report (http://www.oecd.org/department/0,2688,en_2649_34305_1_1_1_1_1,00.html).

[c] According to the World Health Organization (WHO). Described in: Tannenbaum, D. Tackling the big three [contaminated drinking water, untreated human waste, and air pollution]. *Environmental Health Perspectives*, **106**(5), May, 1998, 234–38.

The OECD (Organization for Economic Cooperation and Development) has 29 member states, mostly developed nations including the United States, the United Kingdom and other Western European countries, Australia and New Zealand, and Japan. The conclusions of these two organizations were very similar.

can also be used when comparing pollution issues to non-pollution issues such as the extinction of plant and animal species (Table 2.1).

Comparative risk assessments are difficult undertakings. They are often used to answer questions asked by environmental policy makers and others. Are we spending society's tax dollars in the most efficient way; that is, are we spending more on major risks than on relatively less serious ones? Are there some risks we worry about too much? Answering such questions even imperfectly helps us decide which issues will receive more attention and resources. In fact, that is the major criticism of comparative risk assessments – some are concerned that problems deemed "low priority" may be dealt with inadequately or not at all. Comparative risk assessment goes beyond questions that science can answer and may include evaluations of community values, quality-of-life or economic issues. For example, how important to us is the corrosion of city monuments by acid haze? Or how do we react to an unattractive algal bloom at a popular lake caused by fertilizer runoff? A summary of steps often used in comparative risk assessment is given below.

Choosing issues to compare

Think about being part of a group given the task of comparing environmental risks. You may first ask: What issues shall we compare? This is not an easy question because there are dozens, hundreds of issues. Which will you examine? If you are looking at issues of national scope, you choose those that can affect the whole nation or large regions. Take time to examine Table 2.1, and the issues evaluated. A national group would probably want to rank global climate change as compared with other issues. But if you are examining issues specific to your state or province you may choose to emphasize issues specific to that state. And, if you are examining issues for a city your group might focus on issues immediately relevant to that city such as local hazardous-waste sites, or local air-pollution or water-quality problems. Nonetheless, even local evaluations may also include global issues such as climate change or acid deposition.

Getting technical assistance

Your group will need expert information on each issue. Group members must agree on who the experts are and whether you trust them to give you objective information. For questions that you might expect experts to answer, see Table 2.2. Remember though, that no matter how well informed your experts are there will be information gaps and uncertainties. Typically no further research is done during the risk assessment process to help fill in such gaps.

Making decisions

Once you receive the technical evaluations from your chosen experts, your group examines the information for each risk. What is the quality of the information? What information may be missing entirely? And, *how can you compare risks that seem to have no relationship to one*

Table 2.2 Analyzing environmental risks

Criterion and explanation	Examples
What is the scope of the effect?	
1. How large an area is exposed to the pollutant or problem?	**1.** A region of a state? The whole nation? Or the whole world?
2. How many people are exposed?	**2.** Ten thousand? Millions?
3. For a resource, how much is exposed?[a]	**3.** A small percentage of a nation's forests? Or all of them?
How likely is an adverse effect?	
1. Among people exposed to the risk?	**1.** Small chance that a few people might suffer asthma? Or might many thousands develop asthma?
2. For a resource – how likely is there to be an adverse effect?	**2.** Is acid rain falling on an alkaline soil (and being neutralized), or is it falling on an already acidic soil?
If an effect occurs, how severe would it be?	
1. Among people exposed to the risk?	**1.** Will they suffer no obvious ill-effect from a site containing high levels of lead? Or will children suffer a lowered IQ?
2. On a resource exposed to the risk?	**2.** Will fish in a polluted lake have stunted growth for one season? Or will millions be killed?
What is the trend for a specified pollutant?	
1. Is its concentration increasing, decreasing, or staying the same?	**1.** Is it carbon dioxide with an ever-increasing level? Or, is it dioxins with falling levels in developed countries?
2. What is the pollutant's life span?	**2.** Is it ground-level ozone, which will degrade in a few weeks? Or, a metal, which cannot degrade?
3. Does it bioaccumulate (build up in concentration in animals or plants?	**3.** Is it a chemical easily removed from the body? Or, is it chemicals such as dioxins or lead that accumulate?
What is the trend for other stresses?	
1. Does a resource continue to be degraded? Or has the situation stabilized?	**1.** Do the nation's wetlands (or its forests, fishing grounds, etc.) continue to be destroyed? Or has the loss been curbed?
2. Is the quality of the resource stable? Or does the resource continue to be degraded?	**2.** Are coastal waters able to support fish spawning and growth? Or do they support growth poorly?
What is the recovery time?	
1. Can the environment recover? Or is permanent damage likely?	**1.** Will it be 10 years to recover from an oil spill? Or, 100 years to remove excess atmospheric carbon dioxide?

[a] The word "resource" refers to a natural resource – such as a wetland or lake, forest, fish or other wildlife, soil, etc.

another? How for instance, do you compare "habitat alteration and destruction" to stratospheric-ozone depletion? Or how do you compare air pollution to groundwater pollution? Look at Table 2.2 for some approaches to these questions. Given even the best expert opinion, your group must make judgments. And because members of your group probably represent many backgrounds – e.g., industry, environmental organizations, government, or academic institutions – each may see and interpret exactly the same information differently. Moreover, even as you make judgments, you recognize that your chosen priorities are not absolute, and that others may revisit your work in the future. Nonetheless, many continue to find these exercises worthwhile.

SECTION II

Using legislation to protect nature's services

Laws in the United States

Environmental laws existed before 1970, but none controlled pollution and hazardous chemicals comprehensively. The 1970s saw a dramatic change. In the United States, major laws enacted included the following.

- The Clean Air Act (CAA) in 1970, the Clean Water Act (CWA) in 1972, and the Safe Drinking Water Act (SDWA) in 1974. Legislators then turned to land pollution and passed the Resource Conservation and Recovery Act (RCRA, pronounced "rick-rah") in 1976 to control the management and disposal of solid waste, including municipal and hazardous waste.
- The late 1970s revealed many abandoned hazardous-waste sites around the United States and Congress responded by passing the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) to clean up such sites.
- Toxic chemical laws were also passed. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) in 1972, and the Toxic Substances Control Act (TSCA, pronounced "tosca") in 1976, regulate chemicals not already regulated under the other laws passed earlier. For example, TSCA mandated controls for polychlorinated biphenyls (PCBs), chemicals not covered by other legislation. A major TSCA mandate was to develop an inventory of all commercial chemicals used in the United States. Subsequently, any chemical not on the inventory would be subject to scrutiny by the EPA before it could be used commercially or imported. Passing TSCA was an attempt to "close the circle," to ensure that all chemical issues were addressed. However, the 1984 tragedy in Bhopal, India resulted in the "right-to-know" legislation discussed below. Important international treaties have also been passed. Some of these are noted in later chapters.

End-of-pipe laws

The above laws produced many so-called “command-and-control” or “end-of-pipe” regulations. End-of-pipe regulations can be very effective especially as applied to large facilities. The Clean Water Act (CWA) can illustrate this. When it was passed in 1972, only 30% of American waters were judged fishable and swimmable. By 1994, this figure was greater than 60%. “Fishable” means that fish from the water are safe to eat; “swimmable” means that the water can be used for swimming without fear of infectious organisms or other contaminants at levels potentially harmful to health. After passage of the CWA, industries and cities built many wastewater-treatment plants, and industries began recovering hazardous components from wastewater. In response to other laws, air effluents and hazardous wastes were treated before disposal, and irresponsible waste dumping was greatly reduced. Municipalities and industries designed and built secure landfills to replace old leaking dumps. Controls were placed on motor-vehicle emissions.

Laws in less-developed countries

Controlling pollution and protecting the environmental health of workers is more difficult in less-developed countries. Many of these countries have excellent laws on the books. However, laws are often not enforced because of weak and corrupt governments, and because they lack money to enforce them. Some industries also take advantage of such conditions. An instance is “shipbreaking,” the process of dismantling old ships for scrap metal and other valuables. Shipbreaking was carried out in the United States and Europe until the 1970s. Then, as labor costs and environmental regulations increased, shipbreaking moved to Korea and Taiwan. Lastly, in what is referred to as a “race to the bottom,” it moved to the very poorest countries, including India, Bangladesh, and Pakistan. There, using simple tools such as blowtorches and without worker or environmental protection, hand labor is used to tear ships apart. About 700 ships come to the end of their useful life each year, of which about 90% end up in these impoverished countries.

The picture is not all dismal. A year 2000 “Greening Industry” report from the World Bank[2] notes that some poor countries are finding ways to put pressure on polluters. They use local newspapers and community observers to report on factory behavior. Low-cost computer technology is used to distribute information to communities and to business stockholders. ■ Indonesia’s approach is seen in Table 2.3. Its regulatory agency color codes factories based on their environmental performance, and publicizes the results. Gold is awarded for top performance, green for above standards, blue for

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[2] World Bank. 2000. Greening Industry, Public Information Strategies. http:www.worldbank.org/nipr/pub_info.htm (accessed January, 2002).

Table 2.3 Rating polluters in Indonesia

Performance level	Rating
Gold	Clean technology, waste minimization, pollution prevention
Green	Above standards and good maintenance, housekeeping
Blue	Efforts meet minimum standards
Red	Efforts don't meet standards
Black	No pollution control effort, serious environmental damage

Adapted from the World Bank web site (http://www.worldbank.org/research/greening/cha3new.htm).

minimum standards, red for doesn't meet standards, and black for causes serious environmental damage. When the project began in 1995 with 187 factories, two-thirds were out of compliance with regulations. "Gold" winners were publicly honored while facilities found to be violating standards were given 6 months to clean up before having their rankings made public. When pressured in this way, many more factories complied with the law. Indonesian officials hope to expand this system to include the 2000 facilities accounting for 90% of its water pollution. ■ In the early 1990s, 95% of Columbia's industrial wastes were dumped untreated into receiving waters. After the government started to charge industries and municipalities per unit of water pollution released, many factories and towns began treating their wastewater. ■ China also charges some large factories for the amount of pollution released. In some cases facilities have held pollution constant even as production doubled. ■ The Philippines, India, and Mexico are starting similar programs.

Dishonest individuals can obviously corrupt these approaches. However, as more people become more aware or even involved, and with the promise of positive publicity or the threat of negative publicity, there is more compliance. The World Bank optimistically stated, "After 6 years of research, policy experimentation, and first-hand observation, we believe that environmentally sustainable industrial development is within reach."

Limitations of command-and-control

Almost all US pollution legislation controls pollutants end-of-pipe; that is, capturing pollutants after they are formed. ■ A case in point is an electric power plant. One major pollutant produced by burning coal is sulfur dioxide. The power plant may capture much of that sulfur dioxide from its stack so that it does not enter the air. ■ Or a metal plating firm recovers chromium from its wastewater to prevent releasing it into a river. In these instances, the pollutant still exists, but has been captured so that it can be disposed of responsibly.

End-of-pipe controls cannot recover 100% of a pollutant. An industry or electric utility may remove the first 80% of a pollutant from a waste stream efficiently and cost-effectively. Removing the last 20% may cost 10 times more than the first 80%, and a small amount of the pollutant will still escape into the environment. A specially designed incinerator may destroy 99.99% of the hazardous materials that it burns. For pollutants of special concern, a more costly, technologically sophisticated incinerator can destroy 99.9999%. But the incinerator cannot destroy that last small amount. Even to eliminate the amount they were designed to remove takes frequent monitoring and constant maintenance of equipment. Some believe that the only acceptable amount of a pollutant is zero, which gives rise to the problem of the *vanishing zero*. Analytical chemists constantly devise ever more sensitive methods to detect pollutants. So, even if essentially all of a pollutant seems to have been removed, a newer more-sensitive detection method may find it again. A chemical undetected and unregulated in one year could be detected and regulated the next.

There is a serious limitation to the end-of-pipe approach: the recovered pollutants still exist and must be disposed of. We must incinerate them or bury them in landfills. Or, we strip volatile pollutants from water and allow them to escape into the air. In this case, the water pollutants have become air pollutants. Moreover, the cost to industries of pollution control – recovering, treating, and disposing of recovered wastes – continues to rise. Costs to communities of managing municipal wastes and sewage likewise continue to rise.

Another limitation of command-and-control regulations that industry much dislikes is that "one size fits all." A regulation tells industrial facilities not only to limit the release of specific pollutants, but also tells them exactly how to accomplish that reduction – all facilities must reduce emissions in the same way. But no two industrial facilities are identical and frequently there is more than one way to reach the same end. ■ A *Wall Street Journal* article told the following story some years ago. The AMOCO refinery of Yorktown, Virginia was required to install a $41 million system using a specific technology to capture benzene emissions. However, AMOCO, working with the EPA, found a different method that could capture five times more benzene for only $11 million. But, the law was inflexible and the EPA could not modify requirements, so a greater amount of money was spent to capture less pollutant. In more recent years the EPA is finding ways to allow facilities to avoid the "one-size-fits-all" approach by demonstrating that they can indeed capture more pollution using different methods. ■ In 1995 a *Scientific American* article[3] described regulations intended to ensure that hazardous wastes were safely handled. The automotive industry produced a sludge containing zinc. In earlier years, factories sent the sludge to smelters, and the zinc was

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[3] Frosch, R. A. The industrial ecology of the 21st century. *Scientific American*, **273**(3), March, 1995, 178–81.

recovered and reused. However, in the 1980s, the zinc sludge was listed as a hazardous waste and smelters no longer accepted it. Instead, as a hazardous waste the sludge had to be treated and disposed of in accordance with strict regulations. Clearly, this was an unintended consequence. Most agree that such problems arise because we try to deal with one environmental problem at a time – bit by bit – instead of looking at issues holistically. Given the huge number of detailed regulations that resulted from complex environmental laws, some counterproductive results are inevitable. The US EPA has been working to develop regulations that take into account all the emissions and waste streams issuing from a facility, but they must do this within the constraints of the laws passed by Congress.

A right-to-know law

The world reacted with horror to the Bhopal disaster described in Chapter 1. Then, US citizens discovered that a Union Carbide plant in Institute, West Virginia used the same highly reactive chemical, methyl isocyanate (MIC). This plant also lacked adequate means to keep water away from the MIC. However, after Bhopal it was quickly redesigned. More generally, an important aftermath of Bhopal was the realization that such a disaster could happen anywhere. Recognizing this, the US Congress passed the Emergency Planning and Community Right-to-Know Act in 1986. ■ The legislation required industries and communities to prepare emergency plans to minimize harm in case of an accidental chemical release from a factory, or from a truck or train passing through a community. ■ The law also gave Americans easy access to information on what hazardous chemicals were used in, stored in, or transported through their communities. ■ Another section of the law, the *Toxics Release Inventory* (TRI), provides communities with a new source of information: it requires businesses to make public each year their emissions of any of about 600 chemicals such as ammonia, hydrochloric acid, methanol, toluene, acetone, and lead and cadmium. The TRI does not require that emissions be reduced, only reported. Nonetheless, pressures on industries and municipalities led to a halving of releases of TRI chemicals to air, surface water, and into underground injection wells. An editorial in the journal, *Environmental Health Perspectives*,[4] stated, "This legislation may yet prove to be one of the most important events in the history of environmental health because it instigated the idea that people had the right to know about hazardous agents being manufactured, used, or stored in or around their communities. In a free and open society, the concept of 'right to know' of possible risks to their health seems fundamental."

But the TRI has limitations. ■ A major criticism is that the TRI merely reports the amount of a chemical released. It does not tell

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[4] Hook, G. E. R. and Lucier, G. W. The right to know is for everyone. *Environmental Health Perspectives*, **108**(4), April, 2000, A160.

us how toxic the chemical is. Nor does it tell us whether humans and wildlife are actually exposed to it. In other words, the TRI does not tell us the *risk* of a chemical emission. In fact the environmental organization, Environmental Defense points out that TRI emissions account for only 4% of the total cancer risk nationwide. In contrast, emissions from mobile sources such as cars and trucks, contribute 88% of the cancer risk. Diesel exhaust poses an especially high risk. But motor-vehicle emissions are not reported under the TRI. Thus, the question is raised: Would some different disclosure provide more useful information than the TRI? ■ Other critics note that TRI releases tell us very little about the overall environmental performance of a facility. ■ Despite criticisms, European countries too are developing "right-to-know" legislation that requires corporations to disclose emissions of certain chemicals, and to report what chemicals are transported through communities. Europeans believe these disclosures are a powerful and low-cost means of informing the public. The public may then, as happened in the United States, pressure companies to reduce emissions. Egypt, Czech Republic, and Mexico also have similar programs, but only for chemicals deemed especially hazardous.

Can we completely control pollution?

As noted, the TRI requires industrial facilities to report many legal chemical emissions. In 1988, the first year that TRI emissions were divulged, people were shocked to learn that industry had released nearly 2.6 billion lbs (1.2×10^9 kg) of chemicals into the air the previous year. This is a large quantity, but was only the beginning of the story. About the same time, a nationwide study was carried out on all volatile organic chemical (VOC) emissions into air. The study concluded that 47 billion lbs (21 billion kg) of VOCs were released to the air each year – 18 times greater than 2.6 billion lbs (1.2 billion kg). What were the origins of these VOCs? ■ A portion came from industries not then required to report TRI emissions; these included mining operations, sewage-treatment plants, landfills, and hundreds of thousands of small businesses such as dry cleaners, printers, painters, shops maintaining motor vehicles, even bakeries and food-processing operations.[5] ■ Most strikingly, half of the 47 billion lbs (21 billion kg) came from motor vehicles, driven billions of miles a year by you and me. And, as indicated above, motor-vehicle emissions may pose a much greater risk than TRI chemicals. A new car pollutes much less than one made in 1970, but each year more people drive more vehicles more miles. And many drivers do not maintain their vehicles to run as cleanly as they were designed to run. ■ Individuals also contribute VOC emissions when using charcoal grill

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[5] As one example, about 20 million kg (44 million lbs) of one VOC, hexane is released into US air each year. The source of hexane is its use as an organic solvent to extract millions of tons a year of food oil from soybeans, and to extract millions of tons more from other seeds and grains.

starters, paints, aerosol sprays, pesticides, and many other products. Emissions from one individual alone are small. However, multiply yourself by hundreds of millions – some of these emissions become significant.

Environmental agencies regulate an increasing number of chemicals from a great many sources. But can government regulate every emission? Again, remember motor vehicles. Although these are a major source of air pollution, many people resist testing emissions from their vehicles, or do so resentfully. Could federal, state, and local environmental agencies monitor every small business operation, every home, and every vehicle? What other approaches are available?

Pollution prevention
Reuse/recycle
Treatment
Disposal

Figure 2.1 The waste-management hierarchy

The waste-management hierarchy

End-of-pipe control means capturing the pollutant after it is formed, but before its release into the environment. End-of-pipe control has been called first-generation thinking. A second-generation concept is *pollution prevention* (P^2) – create less of the pollutant or waste in the first place. Better yet, eliminate it. P^2 is at the top of a waste-management hierarchy (Figure 2.1). When P^2 does not work or is not used, the second preference is recycling and reuse. When a material can no longer be recycled or reused, the third step, treatment, is used to reduce the volume or toxicity of the waste. At the bottom of the hierarchy is disposal. The four steps of the waste-management hierarchy are described below.

Steps in the waste-management hierarchy

Pollution prevention

P^2 is source reduction, decreasing the amount of pollution produced in the first place. *Resource conservation* is also P^2, using less of a raw material or increasing the efficiency of its use. Using less energy is resource conservation and P^2 also; pollutant emissions that would result from generating and using that energy are not produced while, at the same time fuel is conserved. The same holds for water and mineral conservation. You may quickly observe that P^2 can save its practitioners money. Illustrations of industry use of P^2 are seen in Tables 2.4 and 2.5. No law mandates P^2, so anyone using P^2 in the United States is going beyond mere compliance with the law.

MINIMIZING SPILLS IS P^2

The first step a company often takes to begin a P^2 program is to evaluate its housekeeping practices. This is true because if a hazardous substance is spilled it becomes hazardous waste and the materials used to clean it up also become hazardous waste. Thus, minimizing spills is P^2. Using less water is P^2; so is using less energy. Using fewer material resources to make a product is P^2; so is reducing pollutant

Table 2.4 Examples of industrial use of P^2

Previous action and result	Change that lessened pollution
Company A used trichloroethane, an organic solvent, to clean metal; discarded trichloroethane is a hazardous waste	Trichloroethane was replaced with a water-based solvent, which worked just as well
Company B painted steel joists by dipping them into open vats of paint; the vats released large amounts of fumes	Paint vats were layered with ping-pong balls, cutting emissions while not interfering with dipping the joists
Company C used energy-inefficient motors; energy was wasted	More energy-efficient motors were purchased as the old ones broke down
Company D packaged detergent in a box too large for its contents; the consumer throws away the packaging	Packaging was redesigned to use less material
Company E manufactured plastic beverage bottles	The bottle was redesigned to use less plastic, but produce an equally strong bottle
Company F is a coal-burning electric power plant; it captured the sulfur dioxide that formed as coal is burned	It found a source of coal with a lower sulfur content

Table 2.5 P^2 in the motor-vehicle industry

A manufacturer designs a vehicle that:	The result is:
Has reduced tailpipe emissions	Less air pollution is produced
Has better fuel mileage	Less air pollution is produced Gasoline is conserved
Is lighter weight, but still safe	Less air pollution is produced Gasoline is conserved
Uses less-toxic chemicals as it is manufactured	Worker exposure to chemicals is reduced Hazardous-waste generation is reduced
Can be disassembled at the end of its life	Some component parts can be reused; others are recycled; materials are conserved; less pollution is produced

emissions when manufacturing the product. Finding less-hazardous chemicals to use in a process when a very hazardous chemical was previously used is also P^2. Reducing worker exposure to toxic chemicals during product manufacture, often called "toxics use reduction," is another P^2 goal.

To make P^2 work, top management must commit itself to its success. At the same time employees are the ones who regularly work with a process. They are often best informed as to where and how to modify a process to decrease pollution. Some companies – 3M Corporation is a prominent example – offer bonuses to employees to develop workable P^2 ideas. Interestingly, after many years of implementing P^2 ideas, 3M Corporation employees continue to generate new ideas – P^2 is an ongoing process.

Questions 2.1

Examine the waste-management hierarchy (Figure 2.1). Then look at Table 2.4.

1. Company "A" effectively replaced trichloroethane with a water-based solvent. How is this P^2?
2. Assume that another company uses trichloroethane as a metal-cleaning solvent too, but uses it once only before discarding it. It finds that it can reuse the trichloroethane several times before the solvent becomes too dirty to perform well. Is there any effective difference in this case between P^2 and reusing the solvent? Explain.
3. What change could Company "D" make so that even less packaging is discarded?
4. (a) What else might Company "E" do to make its bottle more environmentally benign? (b) Where would your suggested change fit on the waste-management hierarchy?

Taking improved housekeeping steps may not be difficult. Other P^2 practices, such as changing from a hazardous organic solvent to a water solvent or changing one step in a production process, may also be implemented without great difficulty. But the rate of return must be high to consider changing a whole production process, because the risk is much greater – more money is spent without complete assurance that the new process will work properly. At its most effective, P^2 involves design for the environment (DfE). In DfE, from the moment that a new product is conceived, it is designed with the idea of keeping its environmental impact low. DfE aims for a product with a longer life, fewer environmentally harmful effects, and easier disassembly at the end of its life for reuse or recycling. We will return to DfE later.

In the United States, only the 1990 Pollution Prevention Act addresses P^2. It does not mandate P^2. Rather it uses the Toxic Release Inventory report to encourage it: when a business reports TRI emissions, it must describe what it is doing to reduce emissions. The EPA and state governments also collaborate with industry to stimulate P^2. In one EPA effort, the 33/50 Program, 1150 participating companies reduced emissions of 17 chemicals that are very toxic or emitted in especially large amounts. Companies reduced emissions at least 33% by 1993 and at least 50% by 1996. In the Green Lights Program, both the EPA and the US Department of Energy work with business and institutions to reduce the energy used in lighting. They also have programs to reduce energy use by other appliances, by industrial motors, etc. Remember though that it is not only industry that can benefit from P^2. Agencies, municipalities, institutions, and individuals can all benefit, e.g., Table 2.6.

Recycling and reuse

Most people are familiar with recycling common materials such as paper, glass, and aluminum cans. The advantages of recycling aluminum are dramatic. Recycling saves 95% of the energy over

Table 2.6 Individual examples of using P^2

You:
- Purchase a car with good fuel economy
- Maintain the car to keep its fuel economy high
- Avoid buying batteries for trivial purposes
- Buy energy-efficient appliances, electronics, and light bulbs
- Turn them off when not in use
- Turn down the thermostat at night
- Eat less meat because less land, energy, water, pesticides, and fertilizers, are used when grain is eaten directly (rather than fed to livestock)
- Practice water conservation in your home and yard
- Purchase durable consumer goods
- Repair appliances and electronics rather than buying new ones
- Buy products with as little packaging as possible
- Drink tap water or beverages prepared at home

Table 2.7 Examples of industrial recycling and reuse

Reuse
- A welding plant does not discard its empty wire spools, but returns them to the supplier, who reuses them
- Engine parts from vehicle engines are refurbished and reused

Recycle and reuse
- An oil refinery refines motor-vehicle oil for reuse
- A paint manufacturer reprocesses waste household paint
- A factory cleans a metal with a solvent, *reusing* the solvent several times
- When the solvent does become dirty, it purifies and reuses it – the solvent never becomes waste
- A factory reuses some of the water it uses in manufacturing its product

Recycle
- A paper maker uses post-consumer paper to make paper
- A manufacturer makes recyclable products, bottles, cans, packaging, etc.
- A manufacturer identifies each consumer plastic it uses in a way that allows the plastics to be separated after use, and recycled into high-quality products

that needed for mining aluminum from scratch and making new containers; recycling also reduces air and water pollution by about 95%. Recycling also serves to conserve aluminum resources. Although less dramatic, savings in energy, resources, and pollution are significant when recycling other metals too. Industrial recycling and reuse examples are given in Table 2.7, and examples of individual efforts

Table 2.8 Individual recycling and reuse

You:

- Recycle every household item that you can
- Recycle not just aluminum cans, but foil and materials made from aluminium
- Find an organization to use your leftover paint rather than disposing of it
- Take used oil and antifreeze to a service or recycling station
- Compost grass clippings and leaves rather than placing them in the trash
- Reuse paper and plastic bags many times over, or, buy fabric bags

are shown in Table 2.8. Reusing a product is usually closer to P^2 than is recycling – fewer resources are needed and less pollution is produced. As an illustration, it takes about one-third less energy to clean and refill glass bottles than to recycle them. However, glass is heavy and the energy saved would be lost if the bottles were transported to a distant market.

Remember that recycling produces waste too, sometimes a great deal. Paper is an illustration. Coatings and fillers amount to as much as 50% of the paper's weight. When recycling paper, these must be recovered and, because they have no practical use, they are disposed of in a landfill. Recycling metal and glass can be continued indefinitely. However, paper or plastic can be recycled only a few times before losing their quality.

Treatment

When a material cannot be recycled or reused, treatment, the third step on the waste-management hierarchy, is used. *There are two important reasons for treating a pollutant or solid waste* – to reduce its volume or to reduce its toxicity (or other hazard). The major reason municipal solid waste (MSW) is burned – considered a treatment – is to reduce its volume. The major reason hazardous waste is treated is to reduce its toxicity. Beyond incineration, there are many ways to treat hazardous waste. Table 12.1 provides a number of examples.

Questions 2.2

1. Other than the examples already given (Table 2.6) what are two P^2 steps that you, as a vehicle owner, could take?
2. Consider the reuse examples in Table 2.7. Give two examples of how reuse and P^2 are similar.
3. Why is reuse ordinarily seen as environmentally preferable to recycling?
4. What are two more examples of recycling at an individual level (not in Table 2.8)?

Box 2.1 German recycling

Germany has a tough recycling law including a program to collect packaging materials. Indeed, so much packaging was collected in the early 1990s that Germany could not recycle it all. The excess was shipped to other European Union (EU) countries, which interfered with recycling programs in those countries. EU countries now forbid member states from setting recycling targets far in excess of what they can handle within their own borders. But the German law had the desired effect – the amount of packaging used went down, 4% in 1993 alone. German manufacturers now tend to package products in glass and paper which are easier to recycle than plastic. Other European countries began in their individual ways to follow Germany's example.

Disposal

Disposal may be at the bottom of the waste-management hierarchy, but responsible disposal is of major importance. Industry must treat a hazardous waste to destroy its hazardous character before disposing of it in a landfill. A municipality must dispose of its MSW and sewage sludge in ways carefully defined by law. No laws apply to how individual citizens dispose of their waste. However, information can be obtained from a library or town office to aid responsible disposal. In the future, if society moves toward industrial ecology (defined below), wastes may be resources.

SECTION III

Beyond pollution prevention

Industrial symbiosis

P^2 is tremendously attractive, but we cannot avoid all waste and pollution. Moreover, pollution prevention alone cannot save land or preserve species biodiversity, both critical issues. In addition to using P^2 we can redefine "waste." Kalundborg, a city in Denmark, is a model of treating wastes as useful byproducts in a process called "industrial symbiosis:" byproducts, whether materials, energy, or water are sold or given to nearby facilities, which use or reuse them (Figure 2.2 and Table 2.9).

- Asnaes is Kalundborg's coal-burning electric power plant. ■ Asnaes uses its high-temperature steam to generate electricity. Lower-temperature steam, which would otherwise become thermal pollution, is piped into 5000 Kalundborg houses and buildings to provide space heating, and also into Statoil and Novo Nordisk to provide them with needed steam. ■ Asnaes uses a scrubber to capture the sulfur dioxide emissions resulting from burning sulfur-contaminated coal – it converts it into *calcium sulfate*, which is sold to Gyproc. Gyproc uses it to make wallboard. Previously, Gyproc

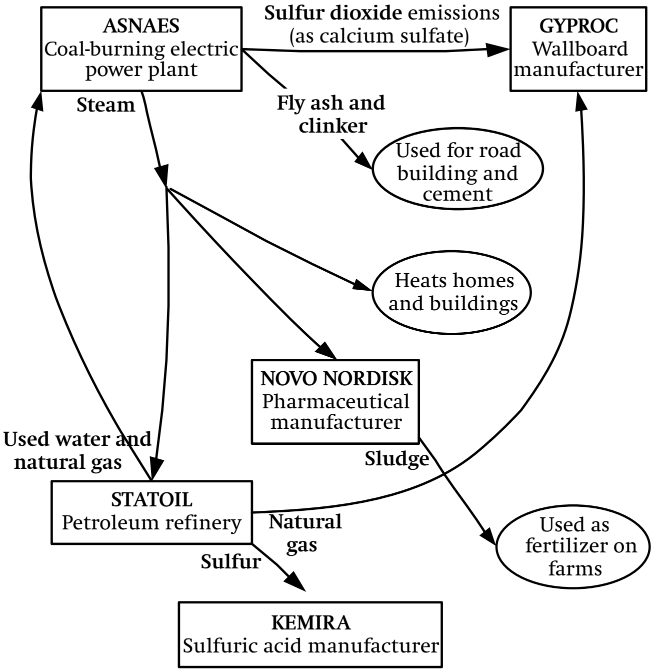

Figure 2.2 Industrial symbiosis in Kalundborg

purchased calcium sulfate from Spanish mines, but now Asnaes meets two-thirds of its needs. ■ Instead of landfilling the fly ash and clinker resulting from burning coal, Asnaes sells them for use in road-building and cement making.

- Statoil is a petroleum refinery. ■ Oil refineries often burn off the natural gas found in petroleum. However, Statoil pumps its gas to Gyproc, which burns it to fire the ovens that dry their wallboard. Gyproc has butane gas back-up for times that Statoil is shut down for maintenance. Statoil also sells gas to Asnaes, so that facility burns gas as well as coal. ■ Natural gas contains sulfur; this is removed by a process producing hot liquid sulfur. This is shipped 50 miles to Kemira where it is used to produce sulfuric acid. ■ Fresh water is scarce in Kalundborg. Statoil pipes its used water to Asnaes, which uses it to clean plant equipment, provide feed water to its boiler, and reduce the thermal pollution that it produces. Overall, town water reuse schemes have reduced demand by 25%.
- Novo Nordisk is a pharmaceutical firm using microorganisms to ferment food-grade material into usable products. ■ Fermentation produces a nutrient-rich sludge. Steam – piped in from Asnaes – is used to kill surviving microorganisms. The sludge is distributed by a pipeline to 1000 nearby farms that use it for fertilizer.

Kalundborg redefined waste and pollutants. “Wastes” and “byproducts” have become useful products. Let’s envision changes in other situations. Think about computers. ■ What if the pollutants and wastes produced as we extract and process the raw materials to manufacture computers could find uses? What if the wastes and pollutants

Table 2.9 | Pollution prevention and industrial symbiosis in action

Facility and problem	Action and result	Facility and problem	Action and result
1. **Los Angeles airport** disposed of 19 000 tons (17 300 tonnes) of food waste a year	• Sends it to sewage-treatment plant where microbes digest it and generate methane • An electric utility burns the methane • Saves waste disposal costs • Make money from selling methane	4. **Bell Helicopter** in Fort Worth used magnesium hydroxide, $Mg(OH)_2$, in electroplating; lost part of $Mg(OH)_2$ to sewer, and it ended up in wastewater sludge	• Pumped sludge back to process; found it could use it 3 to 4 times before dumping • Less sludge to deal with, so saved money • Saves money by buying less $Mg(OH)_2$
2. **ITT Industries**' Virginia facility used sulfur hexafluoride, SF_6, a strong ozone-depleting gas to test tubes in night-vision devices	• Nitrogen was found to work as well as SF_6 without adverse environmental effect • Nitrogen is cheaper to buy than SF_6	5. **International Paper** mill in Jay, Maine generated steam by burning number-6 fuel oil with 1.8% sulfur and other components that become air pollutants	• Natural gas burning facility was built on site; its owner sells steam to the mill • Burning natural gas generates less air pollution and CO_2
3. **Tennessee Valley Authority (TVA)** a large public utility trapped sulfur dioxide as calcium sulfate, $CaSO_4$, and landfilled it; TVA also landfilled fly ash and boiler slag	• Sold $CaSO_4$ to wallboard-making company; eliminates landfill costs and makes money • Sells ash and slag for use in concrete and abrasives	6. **International Paper** mill in Jay, Maine found its wastewater contained mercury, Hg. Traced Hg to purchased products (contaminated acid and alkali)	• Found alternative suppliers to furnish uncontaminated products; wastewater Hg fell to levels no higher than background levels in river

Source: examples 1 to 4, Deutsch, C. H. Together at last: cutting pollution *and* making money. *New York Times*, 9 September, 2001; examples 5 and 6, Hill, M., Saviello, T., and Groves, S. The greening of a pulp and paper mill. *Journal of Industrial Ecology*, **6**(1), 2002, 107–20.

generated during computer manufacture were used? Is it possible for computers, at the end of their useful life, to be disassembled and all components used again? ■ Think more ambitiously still. What if we could blend all man-made products, wastes, and pollutants into the natural ecosystem – without harming it? ■ To make this exercise more than a fantasy we need to change the nature of wastes and pollutants to make them more benign. We need to develop systems in which all biological wastes including sewage become "food" for processes producing useful chemicals. Rather than depleting nature's services, man-made systems could contribute to their viability. Chapter 18 further examines these possibilities.

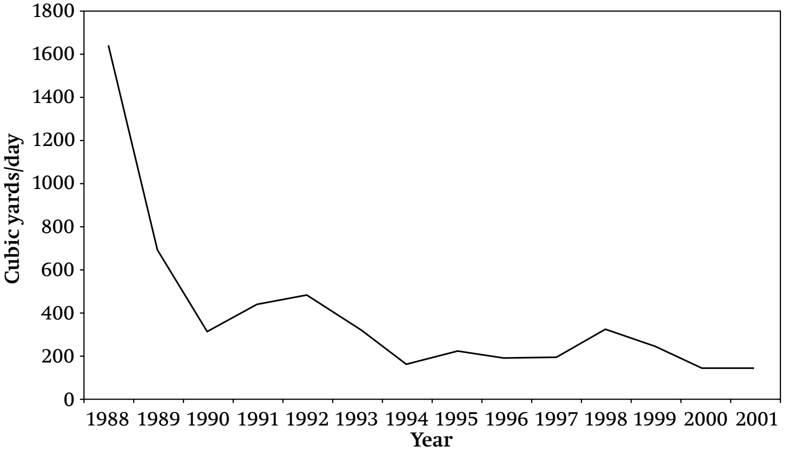

Figure 2.3 Reducing the solid waste that a pulp and paper mill sends to landfill. Credit: The greening of a pulp and paper mill. *Journal of Industrial Ecology* **6**(1), 107–20

Creative waste reductions

Sometimes methods are improvised to solve the problem at hand. See Table 2.9 and the following subsection.

A 91% reduction in solid waste

International Paper's pulp and paper mill in Jay, Maine landfilled an average 1643 cubic yards (1256 m^3) of waste a day in 1988. Efforts at recycling, pollution prevention, incineration, and beneficial reuse reduced waste by 91% to 150 cubic yards (114 m^3) by 2001 (Figure 2.3). The mill now: ■ Recycles wood, metals, and paper. ■ Compacts paper that is non-recyclable into burnable pellets. ■ Uses improved lime-kiln operations to fire all lime mud (previously landfilled). ■ Sells flume grit (dirt and contaminants carried with logs into the mill) to a contractor that processes it into landscape material ■ Burns bark and sludge. The ash produced is not landfilled, but incorporated into AshCrete, a product developed at the mill ■ Also incorporates green-liquor dregs (produced during a recovery operation) into the AshCrete. The only wastes now going to the landfill are MSW types of materials including garbage.

Questions 2.3

1. (a) What are two cases in Table 2.9 that represent pollution prevention? Explain. (b) What are two cases that go beyond P^2 and how?
2. Review Figure 2.2. Now consider facilities in your locale and what possibilities for industrial symbiosis exist? (a) What factors – physical location, financial considerations, liability, and so on – could favor the development of symbiosis? (b) What factors could limit the development of symbiosis? (c) How could materials collected for recycling or landfilling by a municipality become part of a symbiosis scheme? (d) What local agricultural wastes might fit into the scheme?
3. Many believe that American and Western European lifestyles are unsustainable, that per capita resource use is too high by as much as ten-fold. What is an

instance where a technology evolved in a way that reduced its material input by at least ten-fold?

4. What are four products that you could halve your consumption of without affecting your lifestyle?
5. Reduced consumption could damage the economy. What factors could mitigate adverse economic effects?
6. Make a list of the wastes that you throw away on a typical day: (a) in your home; (b) at work; (c) during trips away from home (transportation, lodging, meals, etc.).
7. (a) What wastes do you generate *indirectly* by purchases from the grocery, gasoline station, vehicle maintenance shop, dry cleaners, doctor's office and dentist's office, restaurants, and retail stores? (b) Do you bear any responsibility for these? Explain.

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Chapter 3

Chemical toxicity

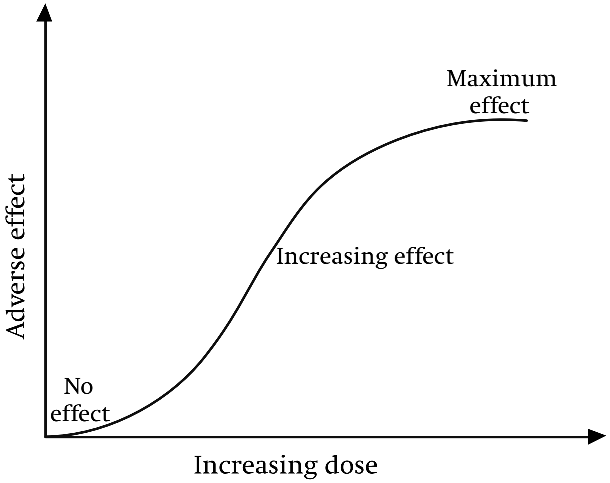
A major reason that we care about a pollutant is that it may be toxic – to ourselves, to wildlife, and to plants, including our crops. This chapter examines the toxicity of chemicals and factors affecting toxicity. **Section I** introduces "the dose makes the poison," and acute and chronic toxicity. It follows a chemical as it contacts the body, is absorbed into and distributed around it, its transformation within the body, and its excretion. Some chemicals are stored and bodily concentrations build up. **Section II** discusses factors that affect toxicity, including gender, age, nutrition, and variation in sensitivity to toxic substances both within one species and between species. **Section III** emphasizes adverse effects that especially concern us. One is those that harm the very young, developing embryos and small children, why they are especially sensitive to toxic effects and often have greater exposures than adults. **Section IV** examines two types of chemicals that concern many people, agents that can cause cancer and those that can mimic natural hormones.

SECTION I

All substances are toxic

Paracelsus, a controversial sixteenth-century physician, was faulted for treating his patients with arsenic and mercury that were known to be toxic. Paracelsus responded with a statement still repeated 500 years later: "All substances are poisons. There is none, which is not a poison. The right dose differentiates a poison and a remedy." That is, a "non-toxic" substance can be toxic at a high-enough dose. And an extremely toxic substance can be safe if the dose is low enough. "The dose makes the poison" is indeed a convenient rule (Figure 3.1). However, there are exceptions to the rule, and many factors other than dose also affect toxicity.

Figure 3.1 Increasing adverse response with increasing dose



Terminology

Table 3.1 gives some definitions of terms used for toxic substances. Sometimes the term "toxic chemical" is used almost as one word, but as the paragraph above has already told you, toxicity is seldom so simple (see Box 3.1). A chemical's effects depend on many factors, including: dose; how fast the dose is given; health, age, and gender of the person or animal exposed; and other conditions of exposure (Table 3.2).

Box 3.1 | Two paradoxes

Vitamin A worldwide

Vitamin A deficiency may cause the deaths of millions of children each year, and hundreds of thousands of cases of childhood blindness. However, large doses of Vitamin A taken by a pregnant woman can cause birth defects such as cleft lip, cleft palate, or major heart defects. For this reason, women of childbearing age are urged not to exceed the recommended daily intake for vitamin A (Figure 3.2). Pharmaceuticals derived from vitamin A can also cause such defects.

Aspirin

Common aspirin is not a nutrient, but has many positive effects. It relieves pain, reduces fever and the inflammation of arthritis, treats and prevents heart attacks and strokes, and may prevent colon cancer. But it can irritate the stomach and can adversely affect children with fever and individuals with blood-clotting problems. It can cause bleeding in pregnant women, and is highly toxic to individuals hypersensitive to aspirin. Aspirin also causes birth defects in rats. Modern drugs are extensively tested before marketing. If aspirin were a new substance and testing demonstrated that it caused birth defects in animals, it would be suspected of doing the same in humans. If available to people at all, it would be as a prescription drug. However, aspirin has been on the market since the nineteenth century and has not been associated with human birth defects. See Table 3.2.

Table 3.1 Definitions

Toxicant	A substance that causes adverse effects in a plant, animal, or human; it does so by impairing vital metabolic functions
Toxin	A toxin is a toxicant produced by a living organism such as a microorganism, plant, insect, spider, or snake
Poison	The word poison is a synonym for toxicant; however, it is a word often used loosely; so is the word "toxin"
Hazardous substance	A hazardous substance may be toxic, corrosive, reactive, flammable, radioactive, or infectious, or some combination of these
Xenobiotic	A chemical foreign to (not synthesized in) the body of animal exposed to it

Table 3.2 Is this chemical toxic or beneficial?

Botulinum toxin	• The most acutely toxic chemical known, which has caused many deaths in people eating improperly processed food • In very tiny doses, it treats muscular spasm and twitching that have responded to no other treatment; it is also used cosmetically to temporarily "relax" wrinkles
Warfarin	• A synthetic chemical used as a rat poison • It is used to prevent strokes and heart attacks
Atropine	• The deadly nightshade plant makes this "supertoxin" • It is used as an antidote for nerve gas and organophosphate-pesticide poisoning
Thalidomide	• A drug that caused tragic birth defects in the 1960s • It is used to treat leprosy, may be used in treating acquired immune deficiency syndrome (AIDS), and is being studied as an immune system suppressant
Curare	• A natural poison, used on arrow tips by Amazon natives • It is used to promote muscle relaxation during surgery
Nitroglycerine	• A chemical used to manufacture dynamite • It is employed to treat angina (spasms of heart arteries)
Sodium chloride (salt)	• A nutrient (essential to life) • It has killed small children who ingested too much; too much leads to retention of body fluids, and is implicated in high blood pressure; chronic eating of highly salted foods is associated with stomach cancer
Nickel and chromium	• Both these metals are nutrients • High doses are toxic and can cause cancer
Nitric oxide	• It is a neurotransmitter produced within the body • It is an ambient air pollutant

Acute and chronic toxicity

"Acute toxicity" is an adverse effect seen soon after a one-time exposure to a chemical. An acute effect may be vomiting, diarrhea, irregular heartbeat, lack of coordination, or unconsciousness. Symptoms might arise in a child who ingested a parent's prescription drug, a farm worker who sprayed a pesticide without proper protection, or

Table 3.3 How do substances exert their toxic effects?

There are many ways that a substance can exert a toxic effect. Three examples follow.

- Carbon monoxide. The blood protein hemoglobin picks up oxygen in the lungs, transports it to the tissues, and releases the oxygen. Because carbon monoxide binds to hemoglobin much more strongly than oxygen it can, when present, block oxygen binding and so lower the amount of oxygen available to the body. If enough hemoglobin is blocked, death results. Lesser doses can cause headache, nausea, and other flu-like symptoms. Chronic exposure is implicated in the development of heart disease.
- Botulinum toxin. This powerful bacterial toxin binds to nerve endings at the points where they join to the muscles. There it blocks the release of acetylcholine, a neurotransmitter ordinarily released by nerve fibers. With no stimulus, the muscles become paralyzed. The immediate cause of death is usually paralysis of respiratory muscles.
- A nerve gas or organophosphate pesticide. These agents do not block acetylcholine release. Rather, once it is released they prevent it from being degraded. The result is that acetylcholine continues to accumulate leading to uncontrolled firing of the nerves.

a teenager who sniffed glue or gasoline vapors. In contrast, "chronic toxicity" results from long-term exposure to lower doses of a chemical or occurs after exposure has ended. Long term may be several weeks or as long as 30 or 40 years. A well-known chronic effect is cancer, which usually does not develop until long after initial exposure. The typical latency period for cancer (the time of initial exposure to the time that cancer is diagnosed) is 15 to 25 years. Leukemia, a cancer of white blood cells, may result from long-term exposure to benzene. Lung cancer may result from chronic exposure to cigarette smoke, liver cirrhosis from chronic alcohol ingestion, or a damaged nervous system from chronic mercury exposure.

A substance that does not cause acute effects may show chronic toxicity. If you break a mercury thermometer, your one-time exposure to elemental mercury vapor is unlikely to hurt you, but chronic exposure to mercury vapor in a workplace can seriously affect the nervous system. Conversely, an acutely toxic substance may not cause chronic effects. The foul-smelling gas hydrogen sulfide is acutely toxic. However, long-term exposure to low doses of hydrogen sulfide, such as the concentrations found naturally in "sulfur waters," is not known to have adverse chronic effects. Indeed, such exposure was once considered beneficial to health.

Dose

Anything is toxic at a high-enough dose. Figure 3.1 shows a dose–response curve, the increasing effect seen as dose increases. Even drinking very large quantities of water has killed people by disrupting the osmotic balance in the body's cells. As the dose of a chemical increases there are many possible toxic effects. Examples are an enzyme that suffers increasing loss of its activity or nerves that become unable to conduct impulses. Table 3.3 illustrates some of the ways in which toxic substances exert their effects.

Table 3.4 Comparing the toxicity of chemicals

Toxicity	**LD_{50}**[a]	**Examples**
Slightly toxic	500–5000	Aspirin, vanillin, salt
Moderately toxic	50–500	Phenobarbital, caffeine, nicotine, warfarin
Highly toxic	1–50	Sodium cyanide, vitamin D, parathion
Supertoxic	Less than 0.01	Atropine, nerve poisons 2,3,7,8-TCDD (dioxin)
Biotoxins	Much less than 0.01	Botulinum toxin, ricin (in castor oil beans)

[a] LD_{50} is the dose killing 50% of the animals exposed to it, expressed in milligrams per kilogram (mg/kg) body weight.

Adapted from: Crone, H. D. *Chemicals and Society*. Cambridge: Cambridge University Press, 1986, 35.

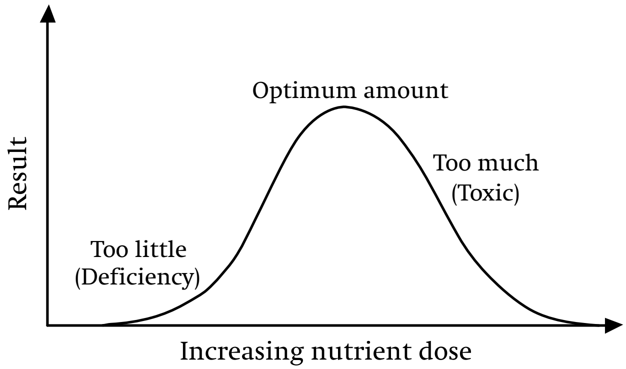


Figure 3.2 Dose–response for a nutrient

Table 3.4 provides comparisons of how toxic one chemical is as compared to another. LD_{50} is measured by noting the dose lethal to half of the animals exposed to it. Determining an LD_{50} is crude, and many consider it cruel. Moreover, it provides little information as to how a chemical exerts its toxic effects. However, people continue to ask how toxic is this chemical? In 2001, an alternative test was announced that uses as few as 6 to 9 rats, instead of the 50 to 200 now used, although results take longer to obtain. A European procedure uses clear signs of toxicity as an endpoint rather than the lethal dose.

Figure 3.2 shows another type of dose–response curve, one for chemicals essential to life such as vitamins, minerals, or amino acids. Adverse symptoms, and even death, may occur if you take in too little of the nutrient. As the dose increases, the animal or plant responds positively up through an optimal dose range. However, if the dose gets too high then adverse effects again occur. Serious illness or death may result if the dose is high enough.

The period of time over which the dose is consumed is as important as the total dose. ■ Taking one aspirin a day for 100 days may be beneficial, but taking 100 aspirins at one time can be lethal. Ingesting one ounce (30 ml) of hard liquor every day for 25 days is fine for most people, but drinking a fifth (25.6 ounces, 760 ml) at one sitting could be lethal. ■ Caffeine is moderately toxic, but people safely drink it. To be lethal, the dose of caffeine in a cup of strong coffee would need to be 100 times higher than it is. ■ Anyone who has chewed a piece of raw rhubarb knows the effect of *oxalic acid* (also found in spinach) on the mouth. But author Alice Ottoboni observed that you would need to eat 20 lbs (9.1 kg) of spinach or rhubarb at one sitting to ingest a lethal dose of oxalic acid. ■ Potatoes make their own insecticide, *solanine*. But to ingest a lethal dose of solanine you would need to eat 100 lbs (45.4 kg) of potatoes at one sitting. However, certain potato varieties (not on the market!) make enough solanine to be toxic to human beings. Potato skin is a nutritious part of the potato but pare away any green skin. Green indicates exposure to sunlight and a higher amount of solanine. Bruised potatoes and potato sprouts also contain higher solanine levels. ■ These examples also demonstrate that potentially toxic substances are found in anything that we eat or drink.

Does the dose always make the poison?

The “dose makes the poison” is a – usually reasonable – corner-stone belief in toxicology. However, if we simply believe that the dose makes the poison, some results can be confusing. This is true because there are instances when a dose that seems very low, can have an effect.

Fetal development

In the case of fetal development, *timing* of an exposure can be crucial. Expose a pregnant woman to a chemical late in her pregnancy, and the chemical probably won’t harm her fetus unless the dose is high enough to harm her too. But go back to the first 8 weeks of pregnancy, and expose her to the same dose: the embryo may suffer serious consequences because it is particularly vulnerable during those early weeks. This was tragically demonstrated by the pharmaceutical drug thalidomide, prescribed to pregnant women in the 1950s. Taken early in pregnancy at doses that did not harm the mother, thalidomide led to babies that often had only stumps of arms and legs.

Environmental hormones

Consider a *hormone*. Hormones are natural chemicals produced in the thyroid, ovaries or testes, pituitary, and other glands. Carried in the bloodstream to target tissues, each exerts effects specific to the hormone. As one illustration, estrogen produced in the ovaries is transported to responsive tissues where it stimulates and maintains changes that make an animal female. At natural levels estrogens and other hormones exert actions vital to an animal’s well being. The estrogen hormone reacts with a specific receptor molecule in its target tissue, and the hormone–receptor complex elicits a response. *Only a tiny dose of a hormone is needed* to react with the receptor although, up to a point, the response increases as the dose increases. However, if the dose continues to rise, negative feedback comes into play and this can turn off the hormone’s effect. So what will happen if an environmental hormone (pollutant) can mimic a hormone? Fortunately, a pollutant is a very weak "hormone" compared with the real one. Nonetheless, wildlife is often directly exposed to such pollutants and sometimes serious effects are seen. Could human development also be affected? This question will be discussed later in this chapter.

Exposure to multiple chemicals

Usually an animal, person, or plant is exposed to more than one chemical at a time. What is the result of multiple exposures?

- The most common effect is *additive*. This commonly happens when all the chemicals exert their effects in the same manner, as when a person is exposed to several organophosphate pesticides at the same time ($1+1+1=3$). Each organophosphate pesticide acts the same way, it inhibits the activity of a specific enzyme. In this case, add up the concentration of each organophosphate pesticide to obtain the total dose.
- *Synergism* presents the greatest concern. When two chemicals act synergistically their combined effect is greater, sometimes much greater, than additive ($1+1$ equals more than two.) An instance is lung-cancer risk from radon. The lung-cancer risk is magnified if a person smokes. In another case, researchers administered a low-dose mixture of lead, mercury, and arsenic to pregnant mice. They observed greater deformities in the fetuses than would be expected by simply adding up the concentrations of the three metals.
- *Potentiation* is another possibility. Chemical 1 does not harm a specific organ, but chemical 2 does. But adding chemical 1 makes exposure to chemical 2 much more toxic.
- *Antagonism* occurs with some chemicals. One chemical interferes with the action of another – it acts as an *antidote*. Consider a child that has ingested a household product or a person who ingested a poison in a suicide attempt. Emergency-room personnel may administer ipecac to induce vomiting, ridding the system of the poison. Or charcoal may be given to absorb the poison, preventing it from crossing the intestinal wall into the bloodstream. Another type of antagonism occurs when two chemicals react with one another to produce a less toxic product. This can happen when a person poisoned with a metal is treated with the chemical dimercaprol, or British anti-Lewisite (BAL), which chelates (binds) the metal ions and prevents them from exerting their toxic effect.

Systemic and local effects

This chapter primarily discusses *systemic effects*. A systemic effect is one occurring at a point distant from where a chemical enters the body. The terms "toxicant" or "poison" most often refer to substances having systemic effects. For example, cyanide exerts its poisonous effects within the body after it has been absorbed; so do snake, spider, or other venoms. However, we need also to be aware of *local effects*. Local effects are those that occur at a substance's point of contact with skin, eyes, lungs, or gastrointestinal tract. An acid for instance irritates (or has corrosive effects) at the point where it contacts the body – it shows *local* effects. A reactive gas such as formaldehyde also has local effects although absorbed into the body it can have systemic effects too. Or, the metal nickel irritates the skin, but after absorption into the body can also exert systemic effects. Some plants have local irritant effects at the point of contact too. This chapter, unless local effects are referred to specifically, discusses systemic effects.

Absorption, distribution, metabolism, and excretion

The acronym ADME may help you to remember what happens to a chemical with systemic effects as it is absorbed into, moves through, is modified by, and leaves the body. A chemical enters the body through the lungs, the gastrointestinal tract, or the skin. From its point of entry, it may be absorbed (A) into the bloodstream, and distributed (D) throughout the body. It is typically metabolized (M) by the body's tissues, and finally excreted (E) from the body.

Absorption (A)

Up to this point the word exposure has been used as if you could suffer an adverse effect just by having a chemical in the environment around you. But, unless a chemical has a local effect on the skin, mouth, nose, or eyes, it must be absorbed into the body. This ordinarily can happen in three ways. You inhale it into the lungs, ingest it into the digestive tract, or absorb it across the skin. Sometimes a chemical gains entry in non-ordinary ways, for example when it is injected into a vein or under the skin. Some xenobiotics (foreign chemicals) are toxic only by one route of entry whereas others are toxic in two or three ways. ■ Formaldehyde can act as a carcinogen only if inhaled. ■ Radon is also primarily a carcinogen by inhalation. ■ However, arsenic is toxic by all three routes: skin absorption, ingestion, and inhalation.

Ingestion

Anything taken into the body by drinking or eating is ingested. Once in the digestive tract, a substance may be absorbed across the wall of the small or large intestine into the bloodstream. Most absorption occurs through the small intestine. From there a chemical enters a portal blood system that carries it directly to the liver. Because the liver is the first organ a toxicant contacts – before it has been much diluted by the bloodstream – the liver receives the highest dose of an ingested toxicant.

Inhalation

Unless you deliberately inject a chemical into the body, inhalation is the fastest means by which a toxic substance can enter the body and exert an effect. Think about inhaling a gaseous anesthetic such as ethyl ether. Anesthesia results very rapidly after the inhaled gas passes from the lung's alveoli into the bloodstream. Many other substances can also be inhaled – think about hot-metal fumes, or the particulates in smoke, or aerosol droplets from a spray can. Because effects can often occur so rapidly, workplace exposures in enclosed spaces can be especially dangerous.

Skin absorption

By stopping or slowing the absorption of most chemicals, the skin provides excellent protection from the outside world. Nonetheless some chemicals are absorbed across the skin, sometimes efficiently. The pesticide parathion is one that is absorbed as rapidly through the skin as by ingestion or inhalation. The chemical *dimethyl sulfoxide* (DMSO) enhances absorption of chemicals that the skin otherwise would not efficiently absorb. When thinking about skin absorption, remember: ■ Thin skin such as found on the abdomen or scrotum is more permeable to chemicals than the thicker skin on the soles of the hands or feet. ■ The larger the area of skin exposed to a chemical, the more that is absorbed. ■ The longer a chemical remains in contact with skin, the more that is absorbed. ■ Chemicals such as acids, alkalis, or metals needn't be absorbed to exert effects; their effect is local.

Distribution (D)

After absorption, a chemical is distributed throughout the body by the blood and is taken up, to varying extents, by different organs. A specific chemical often has a greater effect on one organ than on other organs; this is the organ most sensitive to it, the "target organ". To be toxic, a chemical must reach the most sensitive tissue at a high-enough dose to exert an adverse effect – it is this dose that is important. ■ The nervous system is a major target organ of lead and mercury. However, these metals can affect other organs too as dose increases or time of exposure increases. ■ Benzene, at high concentrations, causes narcosis due to its impact on the central nervous system. Chronic exposure to lower benzene concentrations can result in anemia or leukemia due to its impact on another target tissue, bone marrow. ■ Often substances are stored in the body; if this happens, they don't usually show toxic effects (Box 3.2).

Metabolism (M)

To be able to rid their bodies of absorbed xenobiotics, animals and humans may need to biotransform them into forms that can be excreted. The liver and kidney are especially active in this process. Usually, the xenobiotic is converted into a less toxic chemical. On occasion, the result is a more toxic chemical, for example when the liver converts the pollutant *benzene* into *benzene oxide*, a reactive chemical; it is benzene oxide that damages bone marrow. Animals have always had poisons in their environment, and the biotransformation system that evolved to deal with xenobiotics is an ancient one. From this perspective, modern human-produced toxicants are no worse than the toxins that living creatures have dealt with for millions of years. There are major exceptions, in particular chemicals that the body has difficulty in degrading such as a number of PCBs and dioxins.

Excretion (E)

After exposure decreases or ceases, an absorbed xenobiotic begins to be released. The rate of excretion depends on a number of factors including if and how it has been stored in the body (Box 3.2). A water-soluble xenobiotic is excreted in the urine. If it is not water soluble, the body attempts to biotransform it into a form which is.

- Water-soluble chemicals are largely excreted in urine. Some chemicals such as salt or the xenobiotic sodium cyanide are already water soluble.
- If a xenobiotic is not water soluble, the body attempts to biotransform it into a form which is, then excreting it in the urine.
- Some chemicals cannot be transformed into water-soluble forms. These are excreted with the bile from the liver into the intestine, and exit the body in the feces.[1]
- Volatile chemicals such as ethyl alcohol and acetone are partially excreted on the breath – you may have detected the smell on the breath of a person drinking alcohol. Other gases that you cannot smell such as carbon monoxide are also exhaled.
- The milk of a nursing mother serves as a vehicle for some xenobiotics to leave the body. This sometimes significantly increases the exposure of infants to chemicals such as PCBs and dioxins. ■ Smaller amounts of chemicals are also excreted in sweat.

Box 3.2 | Other important concepts

Bioavailability

Chemicals in the environment such as dioxins, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) bind tightly to soil and sediment particles. They often move into, and become trapped within, a particle's interior. There they are largely inaccessible; that is, they are not *bioavailable*. If an animal ingests such particles, only that portion of the chemical that is not trapped is available for absorption into the bloodstream from the intestine. ■ This is an example of a

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[1] However, part of a chemical excreted with bile may be reabsorbed across the intestine into the blood and carried once again to the liver. It may cycle a number of times before it is completely excreted.

physical factor affecting bioavailability. ■ Chemical factors also affect how much of a pollutant will be absorbed and how fast. Consider that not all the chemical forms of a metal are absorbed equally well. If a person accidentally ingests elemental mercury, little of this water- and fat-insoluble element will be absorbed, and it passes through the gastrointestinal tract into the feces. However, some mercury compounds can be absorbed. *Methylmercury*, which is fat soluble is especially well absorbed – and once within the body is highly toxic. On occasion, chemical differences are used advantageously. The metal barium is toxic, but ingested barium sulfate is safely used in X-ray diagnosis of the colon because it is insoluble, passes through the body, and is excreted. Barium chloride would not be used this way because it is soluble enough that a portion would be absorbed.

Storage

A portion of the chemical distributed around the body may be stored for short or long periods. Even blood stores chemicals by binding them to blood proteins. As long as a chemical remains bound, it does not usually exert adverse effects.[2] When exposure to a chemical is reduced or eliminated, the stored amount usually decreases at a relatively slow rate. However, some conditions result in rapid release. ■ Lead is an important example. It is ordinarily released very slowly over many years from its storage place in bones. During pregnancy, a mother's bones release calcium into the blood to meet the needs of her fetus. At the same time, lead stored in bones is released rapidly and is also carried to the fetus, exposing it to abnormally high lead levels. ■ Fat-soluble chemicals that the body has difficulty in transforming into water-soluble forms are often stored in the fat of animals, birds, and humans and tend to accumulate there. DDT is an example of such a chemical that is usually only slowly released from its storage place in fat. To enhance its rate of release, an experiment was done. Laboratory rats were fed high amounts of DDT for 3 months. No ill-effect was seen in the rats although high levels of DDT accumulated in their fat. Their food intake was then cut in half, forcing their bodies to use stored fat for energy. The DDT stored in fat was rapidly released too, and the rats showed visible symptoms of poisoning. ■ Wild animals go through periods when they use stored body fat. Periods of famine is one instance, but it also occurs when nursing mother animals use body fat for the extra energy needed to produce milk – consider a bear that gives birth during winter hibernation. At these times, pollutants stored in fat may be rapidly released.

Bioaccumulation

When a pollutant concentrates in the body to a level higher than in the environment, the chemical being stored is said to "bioaccumulate." ■ PCBs and dioxins bioaccumulate in fat. ■ Strontium, fluoride and lead bioaccumulate in bones. ■ Metals such as cadmium bind to proteins and bioaccumulate in the liver, kidney, and other soft tissues.

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[2] An exception to this protective effect occurs with radionuclides. Stored or not, a radionuclide can undergo radioactive decay and cause potential harm. Consider strontium-90, a radioactive element found in the fallout of nuclear bombs tested in the atmosphere in the 1950s. Absorbed into the body, strontium-90 was stored in bones, and increased the risk of bone cancer.

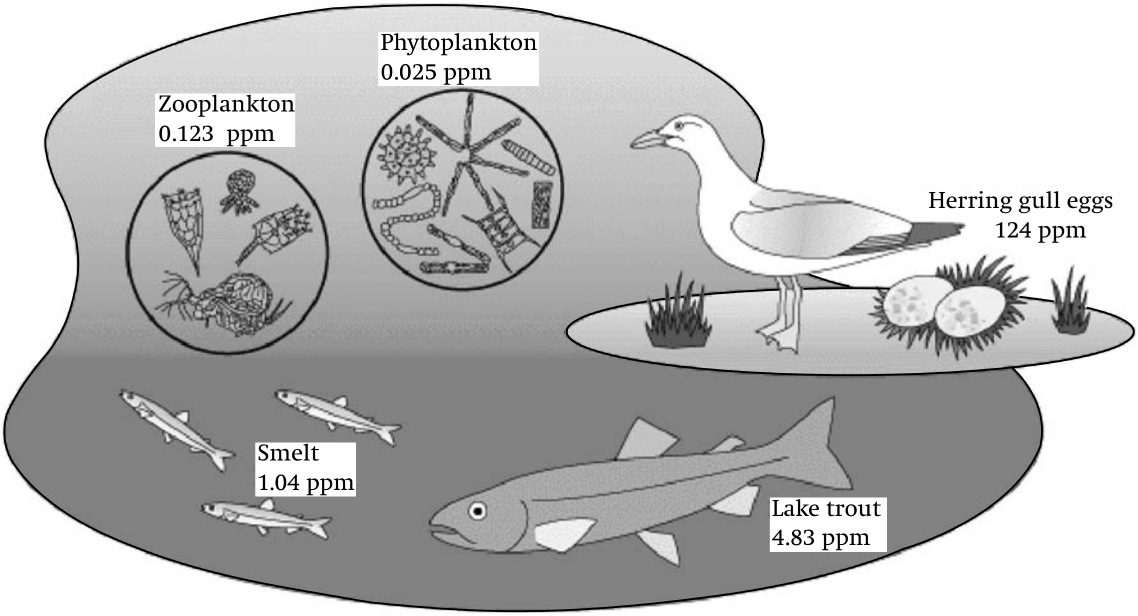

Figure 3.3 Biomagnification of polychlorinated biphenyls. Source: US EPA

Biomagnification

When a pollutant reaches progressively higher concentrations as it moves through the food web, it is said to "biomagnify." Figure 3.3 shows the organic pollutants PCBs, biomagnifying in the Great Lakes food web. Phytoplankton,[3] one-celled plants at the base of the food chain, bioaccumulate PCBs. Zooplankton, small invertebrate animals, eat enough phytoplankton to accumulate PCBs to levels higher than those in phytoplankton. In turn, smelt eat enough zooplankton that their PCB level is greater than that of the zooplankton. Lake trout eating the smelt have higher levels still. The eggs of herring gulls that eat the fish have a PCB concentration higher than lake trout, and dramatically greater than that in the phytoplankton. Not only gulls, but other predators including humans may eat the contaminated fish, and also show very high PCB levels. ■ An especially important example of biomagnification is that of methylmercury (Chapter 15). Bacteria in sediment convert elemental mercury to methylmercury, which then biomagnifies through the food web as shown for PCBs. It may biomagnify a million-fold or more in some birds and mammals (eagles, gulls, seals, minks). ■ DDT and dioxins are other well-known examples of chemicals that undergo biomagnification.

SECTION II

Factors affecting toxicity

How toxic will an absorbed xenobiotic prove to be? This depends on the chemical's intrinsic toxicity (Table 3.4), the dose, dose per

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[3] Plankton are tiny, often microscopic, organisms found drifting near the surface of fresh water and salt water. Zooplankton, tiny animals that include corals, rotifers, sea anemones, and jellyfish, eat the phytoplankton.

Table 3.5 Variation in dioxin toxicity

Species	LD_{50}[a]	Species	LD_{50}[a]
Guinea pig (male)	0.6	Rabbit	115
Rat (male)	22	Dog	30–300
Rat (female)	45	Monkey	70
Hamster	1160–3000	Humans (estimate)	>100

[a] LD_{50} is expressed in micrograms per kilogram (μg/kg) body weight. Information adapted from: Tschirley, F. H. Dioxin. *Scientific American*, **254**(2), February, 1986, 29–35.

time, and other factors that affect toxicity including those considered below.

Species

A chemical that harms one species at a given dose may not be toxic to another.

■ *Silicosis* was a lung disease commonly found in miners exposed to silica dust, but not in their mules which were also exposed. ■ Or, consider Table 3.5. The extreme toxicity of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (also called TCDD or just dioxin) is well known. However, toxicity varies greatly by species. Considering how widespread dioxin is in the environment, humans are fortunate to be less sensitive than many other species. Even so, dioxin poses major concerns.

Variation within a species

Within a given species, individuals may vary greatly in their sensitivity to a toxicant. Some may be very sensitive, others very resistant. Consider aspirin or the sulfites (widely used in wine and food preservation). Some humans are hypersensitive to these chemicals, but there is no indication of adverse effects in most people at levels commonly used.

Gender, age, and nutrition

Gender

The sexual hormones, androgens and estrogens, affect animal anatomy, physiology, and metabolism in many ways, so it is not surprising that the two genders can react differently to a xenobiotic. Women, for example, have less *alcohol dehydrogenase*, an enzyme involved in breaking down alcohol, than do men. Thus, a woman can become intoxicated more rapidly than a man of the same weight. In the past, new drugs were tested only in men. Now, with greater awareness of variations that depend on gender, drugs are tested in both sexes. Moreover, a chemical sometimes affects only the ovaries of a female but not the testes of a male, or vice versa.

Age

The immune system in babies and small children is less well developed than in adults. They often – but not always – are more sensitive to toxicants than adults; see Section III, Children and the fetus. ■ At the other end of life, the immune system of elderly persons may function less well than in younger adults. Thus, the elderly may react more strongly to a drug or pollutant than younger adults. National health-based standards for pollutants and food contaminants are often set to protect the "most-sensitive" populations of which the very young and the very old are major examples.

Nutrition

Good nutrition provides protection against xenobiotics and infectious microorganisms (pathogens). ■ Alcoholics are an example of a poorly nourished population more likely to be affected by xenobiotics and pathogens. People with low-calorie diets or diets with a poor supply of nutrients are another; see Questions 3.1. ■ Individuals who consume high-fat diets have a greater risk of colon and skin cancer. ■ Fat or even "normal-weight" rats and other animals develop more cancer than animals fed a well-balanced, but low-calorie, diet. Obese people have a greater risk of cardiovascular diseases and of a number of cancers. ■ For more examples, see the discussion questions below.

Questions 3.1

1. The metal cadmium is not a nutrient, and can be toxic at low doses. Some years ago, a poisoning occurred in Japan that affected only poor, elderly women living in one locale. Most had several children. Their diet consisted primarily of rice grown in paddies contaminated with cadmium. They developed *itai itai* ("pain-pain"), a disease characterized by kidney damage and brittle, painful bones. Others eating the same diet were not adversely affected. What factors may have caused only these individuals to be adversely affected?
2. Small children are at special risk of lead poisoning in a contaminated environment as they are most likely to ingest contaminated soil during play or inhale contaminated dust. The US Centers for Disease Control and Prevention believes that children with blood lead levels greater than 10 micrograms per 100 milliliters (10 μg/100 ml) are at risk of lead poisoning. As you read the following two cases, recall the term, comparative risk, from Chapter 1.

Case 1: Smuggler Mountain

The area around Smuggler Mountain, Colorado was mined for metals until the early twentieth century. Mining operations left behind large areas contaminated with lead and cadmium. Soil tests in 1982 showed such high levels of lead that the US EPA listed Smuggler Mountain as a Superfund site – a hazardous-waste site posing special risk to human health. The EPA proposed a $12 million clean-up that involved excavating and removing contaminated soil. However, despite the high levels around them, lead in Smuggler Mountain children averaged only 2.6 μg/100 ml of blood. ■ Typically, communities near Superfund sites are anxious to have sites cleaned up thoroughly. However, the EPA's planned excavations could destroy their community, and considering that their children had low blood levels, citizens protested against the clean-up plan. An independent panel of experts evaluated the situation and made recommendations.[4] The panel noted that: Only a few hot spots in Smuggler Mountain had soil containing high lead levels. Grass in summer, and snow in winter, covered the most heavily contaminated areas. Residents had diets high in iron and calcium, which mitigate exposure to lead. The panel recommended a more limited remediation at a cost of only $400 000. One panel member observed: "Lead is not lead is not lead: trying to devise a single clean-up value for soil lead is not practical to use at all sites; each site must be analyzed individually."

Case 2: Lead paint in poorly maintained old houses

Many houses in older US cities were built before the 1970s, and were often painted inside and out with leaded paint. ■ Homes in older inner cities are often poorly maintained, and their leaded paint may be peeling. ■ Once peeled or chipped off, the paint crumbles to dust, which children inhale. ■ Small children may eat the sweet-tasting paint chips or lick the lead-painted sills of windows. ■ Inner-city inhabitants often have low incomes and poor diets.

Compare the risk of lead to children in the above two cases. (a) What are the routes of exposure to lead in old lead-painted houses? Consider air, water, soil, and food. (b) What are the routes of exposure in Smuggler Mountain? (c) Which group of children do you see as most at risk? Explain.

How toxicants affect organs

Toxicants can affect any tissue or organ within the body. However, a specific toxicant often has a "target" organ that is more sensitive to its adverse effects. A few of the organs that toxicants may affect are seen below.

Liver

This organ carries out many vital functions, one of which is to detoxify xenobiotics. The liver is the first organ that a xenobiotic encounters after it is absorbed into the blood from the small intestine – thus the liver is exposed to higher toxicant levels than organs that the chemical reaches after it has been diluted in the bloodstream. ■ Although the liver usually detoxifies xenobiotics, sometimes it converts a chemical into a more toxic substance. One example you have already seen is the conversion of benzene, to benzene oxide. ■ The liver is sometimes exposed to larger amounts of a chemical than it can detoxify, as when a person drinks large amounts of an alcoholic beverage. ■ Chemicals that are toxic to the liver (hepatotoxicants) include organic solvents such as chloroform and carbon tetrachloride. Ethyl alcohol is a well-known hepatotoxicant. Acute toxic effects of excessive alcohol intake are familiar to us all. Chronic effects on the liver of excessive alcohol intake include cirrhosis and cancer. ■ Worldwide, perhaps half a million people a year die from liver cancer despite the fact that most

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[4] US EPA. 2003. Smuggler Mountain [Superfund site]. http://www.epa.gov/region08/superfund/sites/co/smugmtn.html (accessed January, 2004).

should be preventable. The information in Box 3.3 indicates how difficult prevention can be.

Box 3.3 | Reducing liver cancer

Chronic alcohol drinking is the biggest risk factor for liver cancer in the Western world. But much higher liver-cancer rates are found in many poor African and Asian countries. Studies have shown that the major risk factors in these countries are infection with the hepatitis B virus, and aflatoxins – potent liver carcinogens. Aflatoxins are toxins produced by molds, especially *Aspergillus flavus*, growing on peanuts, corn, rice, and other crops. They are also in the meat and milk of livestock that eat aflatoxin-contaminated foods. No person can completely avoid them. People eating a Western diet may ingest 19 ng of aflatoxins per day, but those eating a Far-Eastern diet may consume more than 100 ng. However, if all foods in which aflatoxins are detected were banned, a significant portion of our food supply would disappear. So, in industrialized countries, a food is removed from the market only if it contains aflatoxins at above an "action level." In India, the action level is 30 parts per billion (ppb), in Canada and the United States it is 15 to 20 ppb, and in France and the Netherlands it is 4 ppb. If India used such stringent action levels, already malnourished people would have even less food. Poor countries could probably reduce aflatoxins on foods by improved farming and storage practices and by using pesticides to destroy the aflatoxin-producing molds, but these can be expensive processes.

Now, think about a second risk factor: the risk of liver cancer in people eating aflatoxins increases about 30-fold if they are also infected with the hepatitis B virus. Knowing this could lead to a more manageable way of lowering liver-cancer incidence, i.e., vaccinate people against hepatitis B. But vaccination is too expensive in impoverished countries. Think about some of the implications of this story.

- Microorganisms, in this case the hepatitis B virus, can sometimes cause cancer.
- Interaction of aflatoxins and the hepatitis B virus increases the risk of cancer.
- The risk is accentuated by the malnutrition from which the poor more often suffer.
- Moreover, malnourished persons may receive higher doses of dangerous contaminants than do better nourished individuals.

Kidneys

Like the liver, kidneys can detoxify xenobiotics. However, their major function is to filter the blood, eliminating waste products into the urine while retaining water and nutrients such as glucose. As kidneys filter blood, they concentrate the body's waste chemicals and foreign chemicals as well. The result is that foreign chemicals can reach higher, even harmful doses. Some antibiotics are toxic to the kidneys (nephrotoxicants); so are metals such as mercury, cadmium, and lead.

Immune system

This complex system of tissues, organs, and cells includes bone marrow, thymus, lymph nodes, and spleen. The immune system recognizes the difference between self and what is not self. It rids itself of foreign substances, including microorganisms and cancer cells, using cells that it produces such as lymphocytes and macrophages. A well-functioning immune system also protects individuals against xenobiotics. *Immunotoxic* substances are agents that are toxic to the immune system. They can damage the immune system by suppressing it, or by causing it to overreact. ■ Corticosteroid drugs are among the chemicals that can *suppress* the immune system and damage its ability to fight infections or to remove cancer cells. Drugs suppressing the immune system are deliberately given to people who receive organ transplants to prevent the body from rejecting the new organ. Environmental chemicals such as PCBs, can also suppress the immune system. Individuals with impaired immune systems include the elderly and the sick. People with AIDS, and those undergoing chemotherapy, are particularly vulnerable to infectious microorganisms and chemicals. ■ Substances such as tree and flower pollens can cause immune-system *over-reactions* such as allergies. Certain chemicals cause allergy-like reactions too. Autoimmune diseases such as lupus erythematosus and rheumatoid arthritis also result from overreactions.

The central nervous system

The brain requires high levels of oxygen to function normally, so any substance that lowers oxygen supply is neurotoxic, i.e., toxic to the nervous system. Carbon monoxide is probably the best-known neurotoxic substance (Table 3.3). Some pesticides, including malathion and parathion, nerve gases, and many drugs (legal and illegal), are neurotoxic; so are certain hazardous metals, in particular lead and mercury (Chapter 15), and PCBs (Chapter 14). Especially in children, neurotoxic effects may be expressed in behavior such as attention deficit disorder. Behavioral problems are intensively studied today as they may prove to be a sensitive way of detecting an adverse effect of a neurotoxic chemical.

Skin

LOCAL EFFECTS

There may be local effects of a chemical on eyes and mucous membranes. An *irritant* is one of these. Exposed to an irritating chemical, the skin reacts. The irritation subsides when exposure ceases. Many substances may irritate the skin: a weak acid, such as the acetic acid in vinegar, or a detergent or other cleaning product, the nickel in jewelry, or the chemicals in certain plants. The skin may redden, swell, or itch. Sunlight is an example of a non-chemical irritant; it can cause reddening, pain, and sensitivity. ■ A serious problem may arise when an irritant is also an *allergen*. When an allergic person is exposed for the first time to an allergenic chemical the skin reacts and then recovers when exposure ceases just as in a non-allergenic person. However, expose a sensitive person repeatedly, and the reaction grows in severity. Moreover, reactions occur with much lower doses. An allergy has developed. Formaldehyde, a chemical found in many household products, is an irritant, and also an allergen.

SYSTEMIC EFFECTS

Some chemicals affect the skin indirectly after having been absorbed into and distributed around the body. The antibiotic neomycin, as well as some other antibiotics, can irritate the skin after ingestion; the effects are sometimes severe. Arsenic is a chemical that can have both local and systemic effects on the skin. Systemic effects of arsenic include skin cancer.

Lungs

LOCAL EFFECTS

■ *Reactive gases* such as ozone (found in smog), formaldehyde, ammonia, and chlorine (found in household products) can directly damage the lungs and the mucous membranes in the nose, and can also affect the eyes. ■ Many particles that become airborne can damage the lungs if breathed in and trapped there. Examples are silica, asbestos, coal or cotton dust, and even talcum powder applied too liberally. These substances can be inhaled into the lungs, but not completely expelled. Adverse effects can be acute or chronic. Dust inhalation can have an immediate irritant effect, but chronic exposure can damage lung function; cotton dust exposure over many years gives rise to brown-lung disease, coal dust to black-lung disease, and silica dust to silicosis. ■ A number of substances cause lung cancer. These can be solid substances such as asbestos, or a gaseous chemical such as radon. Chemicals in tobacco smoke may be breathed in as either solid particles or gases. ■ Organic solvents evaporate into the air. Breathing too much of the vapor may damage the lungs. ■ Accidental aspiration of a liquid solvent or of gasoline can severely damage lungs or cause death.

SYSTEMIC EFFECTS

In other instances, lungs serve as the entry point for chemicals that have adverse systemic effects elsewhere in the body. Volatile organic chemicals evaporated from motor-vehicle products or certain household products are breathed in and enter the bloodstream through the alveoli (tiny air sacs deep within the lungs at the end of the bronchiole tubes). The normal function of alveoli is to provide a surface for an exchange between oxygen and carbon dioxide, but other chemicals can follow the same route.

SECTION III

Children and the fetus

Almost any toxic effect can pose concerns, but effects on the developing fetus, baby, or tiny child are perhaps our most profound concern. Children represent our future. One public health expert has said, ". . . the vulnerability of children [is] one of the central public health problems for our time." One major reason for our concern is that children are often more sensitive than adults to polluted environments. They are often more highly exposed to toxicants than adults.

Why children's exposure is greater

Children are often more exposed to pollutants or contaminants than adults. ■ They eat more food per pound of body weight. So, if a food is contaminated they ingest more toxicant pound-for-pound. Pound-for-pound they also ingest more foods such as fruits that have been treated with pesticides. ■ Children often ingest things that adults typically would not, such as sweet-tasting leaded paint and soil. If the soil is contaminated, they suffer greater exposure. ■ Babies and children breathe more rapidly than adults, thus pound-for-pound they inhale a greater volume of contaminated air. One way in which babies and small children are more exposed to air pollutants is at home. Children crawl on or play near the floor, and stir up contaminants into the air that they breathe. Think about an infant living in a city. It, on average each day takes in 110 ng of *benzo[a]pyrene* (BaP), an amount equivalent to smoking three cigarettes each day.[5] The small child is also exposed to the metals, such as lead, and other substances in house dust. Carpets are "deep reservoirs" for chemicals, microorganisms, and allergens (animal dander, dust mites, and mold). This is especially true of old carpets, even regularly vacuumed ones. Exposure can be greatly lowered. Avoid plush and shag rugs, which trap more contaminants. If babies or small children are in the home, use wood or tile flooring. Alternatively, ask people to wipe their shoes at the door. Or, removing shoes can, e.g., reduce the lead in a carpet six-fold. More generally, indoor air pollution can be much greater than pollution in outside air, especially in wealthy countries where outdoor air pollution is controlled (Chapter 17). Indoor pollution may be one cause of the increasing rates of childhood asthma and allergies in urban areas of developed countries, especially as children spend so much time indoors.

Children of the poor

If children in wealthy nations are at risk from environmental exposures, the situation is often much worse for children in undeveloped countries. Those living in cities are often exposed to highly polluted outside air. They are also commonly exposed to polluted drinking water although it is usually the infectious microorganisms in water that pose the greatest risk to them, rather than the chemicals. In rural areas, cooking fuels (wood, manure, or other biomass) are often burned inside the home with poor ventilation. Children and their mothers often have the highest exposure to smoke.

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[5] BaP is the most toxic of a family of chemicals called the PAHs (Box 5.7). PAHs are emitted during all types of combustion, outside and inside the home. Family members track PAHs and other chemicals into the house as dust or dirt on shoes – these settle onto and into carpets, sofas, chairs, and other surfaces.

Why children's sensitivity is often greater

Children don't always show greater sensitivity to a toxicant as compared to adults, but often do. Why? ■ The immune system in babies and small children is incompletely developed, and is less able to fend off toxic insults than those in more mature persons. ■ Children tend to detoxify xenobiotics more slowly than do adults. ■ Children are growing and developing rapidly – and the genetic material, the DNA is rapidly replicating at the same time – giving rise to more possibilities for "mistakes" to occur. Box 3.4 illustrates a situation where children's sensitivity was greater, their exposure was greater, and malnutrition played a role.

Box 3.4 | The Chernobyl nuclear explosion

Radioactive chemicals from Ukraine's 1986 Chernobyl nuclear plant explosion traveled with the winds and were detected around the world. But the greatest problems were within the Ukraine. There, close to the explosion, many thousands left their homes never to return. Ukrainian people somewhat further from the explosion were affected when radioactive iodine settled on vegetation. Cows ate the vegetation and produced milk that children drank. The children began showing an increased rate of thyroid cancer. On the other side of the world, radioactivity was detected but no adverse effects were seen or expected. The explosion exposed millions of individuals to abnormally high levels of radioactive chemicals, including radioactive iodine, I^{131}. The thyroid gland is one of the many organs in children in which cells are replicating more rapidly than in adults. The thyroid takes up the essential element iodine from the bloodstream, and incorporates it into thyroid hormone. Children exposed to I^{131} rapidly absorbed it, along with the usual iodine, into their thyroid glands. There it could induce DNA mutations. The result was a thyroid-cancer epidemic among children. Because cancer takes time to develop, this happened over a period of years. Before 1986, Ukraine diagnosed about 12 cases of childhood thyroid cancer a year. By 1990, thyroid cancers increased to 22 cases per year. From 1991 to 1995 it was 63 cases a year, and in 1996 and 1997 there were 73 cases a year. Children under the age of five at the time of the accident were most likely to develop thyroid cancer. As of 2001, new cases are still arising among those exposed as children in 1986.

So, Chernobyl provides an example of children's greater sensitivity to a toxicant. It is also an instance of children having higher exposures. They had higher exposure to I^{131} because they drink milk, a source of I^{131} because cows ate contaminated grasses and grains. It moreover shows a relationship between malnutrition and sensitivity to pollution; widespread iodine deficiency in Ukrainian diets led to even more rapid uptake of I^{131}.

Protecting children

Only in recent years has one of the world's wealthiest countries, the United States, begun efforts to provide extra protection to children from potentially unhealthy exposures, above and beyond that provided to adults. In 1993, a National Academy of Sciences panel[6] recommended that children be given an extra ten-fold safety factor when setting tolerance levels for pesticide residues on food. Subsequently, in 1996 the US Congress passed the Food Quality Protection Act telling the US EPA that – unless evidence exists to the contrary – it should provide that extra ten-fold safety factor for children's exposure to pesticides. Box 3.5 shows what can happen when children are not protected.

Children have many exposures in addition to pesticides. In 2000, the US EPA asked chemical companies to evaluate 23 chemicals that monitoring programs had found in the environment and in human tissues. As of 2001, 35 companies volunteered to evaluate the chemicals for potential health effects in children. However, in addition to these 23, there are thousands of high-production-volume chemicals – 15 000 are produced in quantities over 10 000 lbs (4536 kg) each year in the United States. For most of these, there is no information available to compare reactions of children and adults. Recently, large-scale testing programs have begun that aim to provide toxicity information on thousands of chemicals. These will also provide information useful for evaluating children's exposure.

Box 3.5 | "Picturing pesticides' impact on kids."

Farmers in Mexico's Sonora Yaqui Valley apply pesticides 45 times per crop cycle, and often grow two crops a year. Many Yaqui Indian families in the Valley also regularly use insecticides in their homes. Thus, it was probably not surprising that investigators found detectable levels of many pesticides in the blood of babies born to these families, babies further exposed to pesticides through their mothers' milk. Dr. Elizabeth Guillette and colleagues examined the behavior of 33 heavily exposed children. They compared them to 17 Yaqui children from nearby foothills, whose only major pesticide exposure was to DDT that the government sprayed to control malaria. Figure 3.4 shows the astonishing difference between these two groups of small children when they were asked to draw pictures of people.

Heavily exposed children were impacted in other ways. They showed less stamina than unexposed children when asked to jump up and down as long as possible, catch balls, or perform simple tasks, and their memories were impaired. One scientist after examining the study said, "The implications here are quite horrendous," and the magnitude of the observed changes "is incredible . . . and may prove irreversible." See article by Raloff in Further reading.

In the United States, and other industrialized countries also, there is continuing concern about children's exposure to pesticides, particularly farm children and the children of migrant agricultural workers. The US General Accounting Office recommends educating farm-worker parents about how agricultural pesticides can affect young children. Pesticide labels should specify the period of time that children should stay out of fields after spraying. Currently, in the United States there are also efforts to reduce or, when possible, eliminate the use of pesticides in schools.

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[6] Cooney, C. M. New pesticide law drops "zero tolerance" standard, focuses on exposures to children. *Environmental Science and Technology*, **30**(9), September, 1996, 380A.

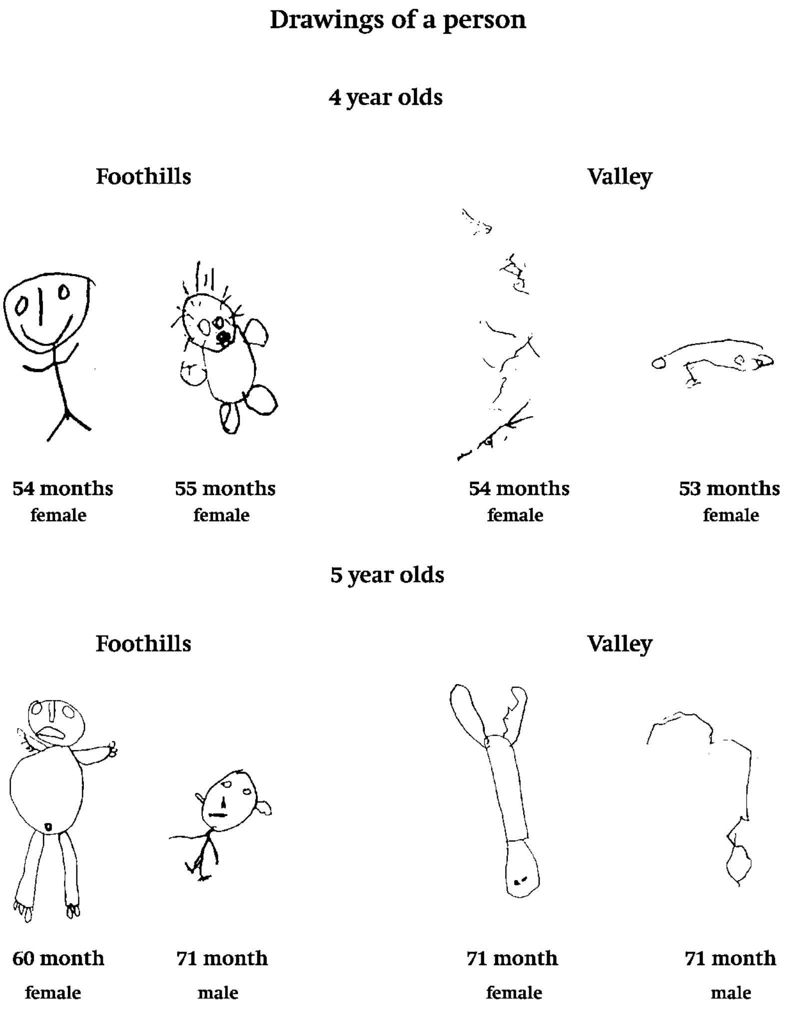

Figure 3.4 Picturing the impact of heavy pesticide exposure. Credit: Dr. Elizabeth A. Guillette, University of Florida, Gainesville

Before birth and postnatal exposures

Preventing exposures to xenobiotics is even more important for the developing embryo and fetus in the womb, and for the baby. Normal development requires a very complex set of processes that require precisely regulated coordination. Several environmental-health specialists comment that, "Recent . . . findings make clear the exquisite sensitivity of prenatal and postnatal periods." Xenobiotics are not the cause of most birth defects – but saying this cannot allay the major concerns on this subject. And, adverse effects on the embryo or fetus may not cause obvious birth defects, but may still be responsible for diseases, such as cancer, that develop later. See the account of diethylstilbestrol below. There are fears that an increase in testicular cancer seen in young men may be due to prenatal exposures. Because environmental hormones, discussed below, may act at extremely low concentrations, even tiny *in utero* exposures to suspect chemicals leave us uneasy (Box 3.6).

Box 3.6 When timing is at least as important as dose

A *teratogen* is a toxicant, which can kill the embryo or fetus or cause damage that may result in mental retardation, deformed organs, or other birth defects. The embryo (through about the eighth week of pregnancy) is especially sensitive. A given dose of teratogen is most likely to cause damage when an organ that it can adversely affect is developing. The same dose may cause no harm later in the pregnancy. An example is thalidomide, a drug given to pregnant women to prevent nausea in the 1950s and 1960s. Thalidomide didn't harm the women taking it. However, taken early in pregnancy, it led to babies born with major defects such as having only the stumps of arms or legs. Taken later in pregnancy, the same amount of thalidomide caused no harm.

Because of the sensitivity of the fetus, pregnant women are advised to avoid alcohol, tobacco, and almost all drugs, indeed to avoid large doses of almost anything. Even the nutrient vitamin A can cause birth defects when taken in above-recommended doses. Young women are advised to avoid suspect substances, not just during pregnancy but whenever a pregnancy is possible, because the sensitive development period may have begun before a woman even realizes she is pregnant. In these situations it is fetal health that is affected, not the mother's health. However, if the mother's health is poor, that can also affect development. A mother's malnutrition can also adversely affect fetal health.

Exposure of fathers to certain xenobiotics can damage their germ cells. In males, the insecticide *dibromochloropropane* (a soil fumigant used as a nematocide) can damage sperm chromosomes and lead to sterility. Lead (often called a toxic element or heavy metal) can produce malformed sperm.

SECTION IV

Dreaded diseases

We dread the thought of hurt occurring to our babies and children; but we also dread potential harm to ourselves. We dread cancer and, more generally, "unknown agents" that may be in our environment.

Environmental hormones

Hormones are profoundly important to reproduction, sexual identity, development, and metabolism. This means that if individuals are exposed to *environmental hormones* – hormone-mimicking pollutants in the environment – there are countless ways that damage could ensue. Environmental hormones are also called "hormonally active agents," "endocrine disrupters," or "hormone mimics." It is not only certain industrial chemicals that have hormonal activity. Some pharmaceuticals are hormonally active. Some plants produce phytoestrogens that have activity similar to human female hormones. Environmental hormones may be active at very low doses and if harm occurs, it may not be apparent until many years later. After the lapse of many years it is very difficult to trace back to causes.

A human effect

The potent synthetic estrogen *diethylstilbestrol* (DES) was a pharmaceutical prescribed to pregnant women in the 1950s and 1960s to prevent miscarriages. DES caused no toxic effects in the women taking it. But, 15 to 25 years later, an epidemic of a rare cancer of the vagina occurred among young women. With difficulty, because of the time that had passed, the epidemic was traced to the mothers of these young women, who had taken DES when pregnant with them. This was a major and disturbing finding: cancer in adults could develop as a result of *in utero* exposure many years before.

However, DES is more potent than even natural estrogens whereas environmental hormones are typically very weak. In addition, DES was deliberately given in pharmaceutical doses as compared to typically very low environmental exposures. But as this story develops, notice that it is reasonable to hypothesize that humans may also be affected by environmental hormones.

Animal effects

Unlike diethylstilbestrol, only animals are known to have suffered harm from environmental hormones. Wildlife, animals, and plants are typically more highly exposed to the pollutants we humans release to the environment than are humans. Several environmental hormones are known to have harmed wildlife reproduction and development. ■ There is a notorious example, with which you may be familiar, that of the once commonly used insecticide DDT. Because DDT does not easily break down, its environmental concentration built up greatly over the years it was used. Eagles, osprey, and several other birds exposed to DDT, had thin eggshells, which were often crushed before they could hatch; this greatly reduced the populations of these birds by the 1960s. DDT also led to a major population drop in Western sea gulls, but not as a result of eggshell thinning. The gulls laid eggs that produced sterile males, or else male birds with feminized reproductive tracts or other feminine characteristics. Industrialized countries banned DDT in the 1970s, and many bird populations slowly rebounded. Recovery was slow because DDT and dichlorodiphenyldichloroethylene (DDE) (a DDT breakdown product) persist for so long in the environment. ■ Another infamous case resulted from a large spill of the pesticide dicofol into Florida's Lake Apopka in 1980. The dicofol was later found to have a major contaminant, 15% DDT. Subsequent observation showed that, compared to a normal hatch rate of 70 to 80%, only 5% of Lake Apopka's alligator eggs were hatching, and many of these died within weeks. Many survivors had feminine characteristics. These effects on alligators were traced to *p, p′*-DDE, a breakdown product of DDT.

Estrogens and other hormones

Estrogens are female hormones made primarily in the ovaries. Quite aside from environmental hormones with estrogenic activity, millions of women deliberately take pharmaceuticals with strong estrogen activity, i.e., birth control pills and hormone replacement therapy. Both genders are also exposed to natural plant estrogens. Phytoestrogens (plant-produced chemicals) are found in baby formula for infants unable to tolerate milk. Infants drinking soy-based formula may be exposed to doses of *isoflavones* between 6 and 11 times greater than those known to show hormonal effects in adults. Effects are not necessarily adverse, but soy-based infant formula is under suspicion and is being studied for possible long-term effects. ■ Moreover, a great many young men deliberately take androgens (male sex hormones) to accentuate their athletic abilities. ■ Beyond estrogens and androgens, other hormones such as thyroid hormone produced by the thyroid gland are widely used as pharmaceuticals. ■ The fact that so many millions of people take hormones makes it especially difficult to sort out how industrial environmental hormones may fit into the picture.

Effects in human embryos?

Only animals – to our knowledge – have been affected by environmental hormones, but many ponder whether humans are also harmed. The University of Florida's Louis J. Guillette Jr. did much of the work exposing DDT's effects on alligators. He warns that the wildlife abnormalities we have seen mean that we must also look carefully for effects in humans. A debate developed in the 1990s, and continues today, as to whether environmental hormones are a danger to developing human embryos.

Responding to the risk

In the mid-1990s the US Congress asked the National Research Council (NRC) to review current knowledge of hormone-mimicking pollutants. An NRC committee scrupulously examined the literature looking for evidence that environmental hormones could be harming human reproduction, development, or neurological and immune systems. The NRC reported in 1999[7] that humans and wildlife are routinely exposed to hormonally active agents via food, water, soil, and air. Active agents include many synthetic chemicals and plant estrogens. The NRC committee said it needed much more information before concluding that environmental hormones were a danger to humans. However, well-known researcher Frederick vom Saal

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[7] National Research Council. *Hormonally Active Agents in the Environment.* Washington, DC: Academy Press, 1999.

commented, “The absence of information can’t be used to say these chemicals are safe.” So what to do? The NRC committee emphatically stated that we must be diligent in continuing to monitor the suspect chemicals in the environment, in wildlife, and in humans. Committee members also wanted to see continued study of animal and human populations for evidence of adverse effects including: disruption of normal reproduction and development, declines in fertility, increased incidences of cancers, and possible population declines in wildlife species.

Not just DDT, but more than 100 industrial pollutants are already known or suspected of being, environmental hormones. Among these are a number of pesticides, phthalates (see below), bis-phenol, several metals, and the metalloid arsenic. ■ In 1996 when the US Congress passed the Food Quality Protection Act and reauthorized the Safe Drinking Water Act, it ordered the US EPA to screen the 87 000 chemicals in commercial use as to whether they had hormone-mimicking activity. This is a gigantic task. Before the EPA could even start screening for activity, it had to develop the assays needed to fulfill that task. ■ There are also many ongoing research studies in the United States and around the world. ■ An international risk-reduction measure was taken in 2000 with an international treaty, which bans or severely restricts 12 persistent organic pollutants worldwide, the “dirty dozen.” Rather than banning DDT, it was severely restricted. It is still used to “paint” walls in homes to kill mosquitoes in locales with major malaria problems. Many of the “dirty dozen” have environmental hormone activity. A number were pesticides. Many, like DDT are polychlorinated, that is, have a number of chlorine atoms as part of their chemical structure.

The phthalate example

About a billion pounds (454 million kg) of chemicals in the phthalate family are manufactured worldwide every year. *Phthalates* are used as plasticizers (softening agents) in children’s polyvinyl chloride toys and teething rings, and in medical products. They are used in paints and varnishes, and are common in many cosmetic and toiletry products including nail polish, soaps, shampoos, and perfumes. Depending on the product being used, and the phthalate it contains, people may inhale phthalates, or else ingest them as they leach from plastic products onto food. Phthalates may also be absorbed across the skin. That they do get absorbed into the body was verified in a study performed by the US Centers for Disease Control (CDC) who found phthalates and their breakdown products in human blood and urine. But, remember that modern analytical methods often detect remarkably small amounts of a chemical. So, even for chemicals active at low doses, detection alone means little, and the CDC believes that the levels of most phthalates are not a health threat. However, two were detected at levels higher than would be expected on the basis of their production volume.

Recall that exposures of the embryo, fetus, and tiny child are our major concern. In one study, researchers exposed rodent fetuses to phthalates at a time that would correspond to the end of the first trimester of pregnancy in humans. Experimental results showed lower than normal levels of testosterone in the male fetuses, and reproductive and developmental problems. The question of course arose: Could the reproductive development of human male fetuses exposed to phthalates also experience disruption? Or, could the rapidly developing organs of babies and tiny children be affected? The US National Toxicology Program convened a panel of 16 experts to help answer these questions. The panel concluded that most phthalates posed little concern although – as usual – there was not enough information to make absolute statements on safety.[8] ■ One phthalate does pose a major concern, *di(2-ethylhexyl) phthalate* (DEHP). DEHP is used in intravenous bags and tubing, and can leach from the bags into the fluid they contain. Thus, DEHP can directly enter the bloodstream. In particular, DEHP poses risks to the developing reproductive tracts of critically ill male infants who sometimes have prolonged exposure through intravenous bags. Newborns, with developing testicles, are believed to be at the greatest risk. The US National Toxicology Program and the FDA expressed concern about DEHP in medical devices, and environmental organizations called for hospitals to use alternatives. Meanwhile, Health Canada issued a strong warning in January 2002 that medical devices containing DEHP should not be used to treat infants, young boys, pregnant women, and nursing mothers. Alternative products are available.

Cancer

Many diseases with potential or real environmental causes concern us greatly. One of the greatest concerns is environmentally caused *cancer*. The word cancer describes cells growing abnormally, multiplying in the absence of the usual controls. Chronic alcohol drinking is associated with liver cancer; so are the aflatoxins produced by molds growing on grains. Smoking tobacco is associated with lung cancer. Chronic benzene exposure in the workplace is associated with leukemia, a cancer of the white blood cells.

How can a carcinogen, a cancer-causing agent, cause cancer? A chemical that reaches the cell's nucleus may mutate the genetic material (deoxyribonucleic acid, DNA). Before a cancer develops, the DNA may suffer many mutations. Normally, DNA repair enzymes repair many of these. Repair enzymes, a natural defense system evolved over eons. The enzymes do not distinguish between mutations caused by synthetic carcinogens and natural carcinogens, they just repair the damage. Certain carcinogens in trace amounts can sometimes cause cancer, but it is typically higher doses of carcinogens that overwhelm

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[8] Booker, S. M. National Toxicology Program Center reports on phthalate concerns. *Environmental Health Perspectives*, **109**(6), June, 2001, A258.

Table 3.6 Cancer development

Cancer initiation (inducing a mutation)

- An initiator (benzopyrene is an example) reaches a cell's DNA:
  - it forms an adduct with DNA, that is, it reacts with, mutates the DNA
  - it is genotoxic, that is, it damages the DNA
- For a tumor to grow, a number of mutations are necessary:
  - many mutations are repaired by DNA repair enzymes
  - but if not repaired then, when the cell divides, the mutation replicates too
- The US EPA treats a cancer initiator as having no threshold (no safe dose), whereas European agencies may assume the carcinogen does have a threshold (a safe dose)

Promoting the cancer

- The tumor (neoplasm) grows from the cell or cells with mutations that were not repaired
- A promoter (chloroform is an example) enhances tumor growth, but does not damage DNA

A complete carcinogen can both initiate and promote tumor growth.

Cancer progression

- As the tumor grows additional changes occur in the DNA
- If the tumor is benign, it does not invade other tissues
- If the tumor is malignant, it may spread (metastasize) to other tissues

repair mechanisms. The higher the dose the greater is the likelihood of damage.

Cancer development

Carcinogens that directly interact with and mutate DNA are called *initiators* (Table 3.6). Theoretically, an initiator has no threshold, no safe dose. A cancer could be caused by any dose greater than zero. But notice that there is a difference between a trace dose in the environment and having that trace dose absorbed into the body, reaching a target tissue, and then reaching the nucleus within a cell at a level able to exert damage. Other carcinogens are *promoters*. A promoter has effects within the cell that promote the growth of an already initiated cancer. Promoters do not directly affect DNA, and they do have a threshold. A dose below that threshold does not promote cancer. Some chemicals are *complete* carcinogens in that they both initiate and promote cancer.

Some US cancer rates have increased, and others have decreased. Breast- and skin-cancer rates have gone up while stomach-cancer rates have decreased. The risk of cancer increases with age, and by the age of 85 about one-third of people will have developed cancer. Thus, as the numbers of older persons increase, so does cancer incidence. About one in three Americans is diagnosed with cancer in his or her lifetime. About one in five will die of cancer. Lifestyle plays an important role in cancer development, see Box 3.7.

Box 3.7 | Causes of cancer

- Tobacco. About one-third of all cancers are associated with tobacco use.
- Diet. Almost another third is due to diet. Too much fat or too little fiber is associated with an increased risk of colon cancer, and possibly skin and prostate cancer. Chronic high-level consumption of salted and pickled foods is associated with stomach cancer. Obesity also increases the risk of several cancers.
- Alcohol. Heavy alcohol consumption increases the risk of liver, colon, and breast cancer.
- Sunlight. Excessive exposure to the sun's ultraviolet light heightens skin-cancer risk.
- X-rays. Medical and dental X-rays are a risk factor for leukemia.
- Viral infections. The human papilloma virus enhances cervical cancer risk. The hepatitis B virus enhances liver-cancer risk. In countries where hepatitis B infection is common, liver cancer is also common. Worldwide, this virus is second only to tobacco as a carcinogen, but its influence is much less in developed countries.
- Bacterial infections. The bacterium *Heliobacter pylori* heightens stomach-cancer risk. Other associations of bacteria with specific cancers are being investigated.
- Sexual habits. The human papilloma virus (HPV) is associated with cervical cancer, especially in women who have had, or whose husbands have had, multiple partners.
- Occupational pollutants. Examples are high benzene exposure and leukemia, and high vinyl chloride monomer exposure and liver cancer.
- Environmental pollutants. Examples are: tobacco smoke, very fine particles, and radon, and their association with lung cancer; arsenic associated with skin and several other cancers. Other relationships are seen throughout this book. One study made a worst-case assessment of the combined risk of known environmental carcinogens, and concluded that 1 to 3% of cancers may be due to pollution. Epidemiological studies arrived at a similar figure. However, as knowledge of cancer grows, this percentage could change.

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Chapter 4

Chemical exposures and risk assessment

"We have inadvertently acquired a great deal of influence over the future habitability of the planet. At issue is whether we can assume the responsibility to go with it."

Lester R. Brown, Worldwatch Institute

How much ozone should we allow in the air we breathe? How much arsenic in drinking water? What level of dioxin in soil or food? These and similar questions arise every day. And, because we seldom have the luxury of answering "zero," we must determine what level above zero is safe or essentially safe. The still-imperfect tool of chemical risk assessment assists us in this effort. To undertake a chemical risk assessment, we must first learn about our exposure to the chemical, a topic probed in **Section I**. Then **Section II** reviews epidemiological studies, investigations designed to detect relationships between human exposure to a chemical and adverse health effects. **Section III** introduces the four steps of chemical risk assessment. In **Section IV** we see what risk managers do with this information, how they explore ways to reduce or eliminate a chemical's risk. We also briefly examine exposures in impoverished countries.

SECTION I

Keep in mind the distinction between hazard and risk. You need to care about a hazardous chemical only if it becomes a risk. It only becomes a risk if you are exposed to it. A hazard by itself is only a potential risk:

$$\text{Risk} = \text{Hazard} \times \text{Exposure}$$

That is, no matter how intrinsically toxic a chemical is, you must be exposed to it to be at risk. Then, to evaluate the risk, you need to know the inherent toxicity of the chemical to which exposure is occurring, how much exposure is occurring, and other conditions of exposure.

Exposure

Thousands of industrial chemicals exist. Many are hazardous and could pose a risk. To protect yourself ask first: Am I exposed to it? If so, to what amounts? What is the route of exposure, i.e., does the chemical reach you in air, water, soil, or food? You have seen several illustrations of exposures to hazardous chemicals in earlier chapters.

- Children and lead at Smuggler Mountain and in houses with crumbling lead paint. Routes of exposure included inhalation of leaded dust, ingestion of leaded soil or paint, or of lead-contaminated food.
- Babies and benzo[*a*]pyrene. Routes of exposure were inhalation of dust and dirt as they crawled on contaminated carpets, or ingested these in hand-to-mouth activities.
- Ukrainian children and radioactive iodine. Milk drinking was the major exposure route.
- Yaqui Indian children and pesticides. Routes of exposure were inhalation of sprayed pesticides, and eating food and drinking water contaminated with pesticides.

Or think about dioxins.[1] Typical routes of exposure to dioxins follow. ■ Combustion. Dioxin forms during poorly controlled combustion in municipal-waste incinerators and other combustion sources. Dioxin particles released to air settle onto vegetation where they are then eaten by cattle and other animals. Animals concentrate dioxins in their fat. Humans receive about 90% of their total exposure when they eat contaminated fatty meat such as hamburgers and fatty dairy products. ■ Chlorine-using processes. A pulp mill still using elemental chlorine to bleach pulp may release small amounts of dioxins in their effluent. Released into a river, the dioxins attach to sediment particles. Bottom-feeding creatures ingest dioxin as they eat the tiny organisms living there and the dioxins biomagnify in the food web (Chapter 3). Fish that eat the contaminated organisms concentrate dioxin in their fat and larger fish concentrate still more. Birds of prey, large mammals, and humans are exposed when they eat the contaminated fish.

Questions 4.1

1. Through what environmental media – air, water, soil, and food – can you be exposed to pesticides? Explain how each exposure could occur.
2. Through what environmental media can you be exposed to radon, the radioactive gas?

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[1] Dioxins and furans are a family of chemicals. The most toxic is 2,3,7,8-TCDD, often just referred to as dioxin.

3. (a) People living in a home with peeling lead paint are exposed to lead in several media. What are they? (b) If there is lead in the plumbing how would exposure occur?
4. What chemicals could a baby or small child be exposed to in its toys?
5. When you use cosmetics or toiletry items, are you exposed to synthetic chemicals? Explain.
6. Would exposures to natural chemicals necessarily be safer? Explain.

Body burden

We humans are exposed to chemicals in air, water, and food. Does exposure mean that the chemical becomes a *body burden*; that is, is it actually absorbed into the body and detectable in blood or urine? In 2003, the US Centers for Disease Control and Prevention (CDC) released its second *National Report on Human Exposure to Environmental Chemicals*[2] with results on levels of 116 pollutant chemicals in human blood and urine collected in 1999 and 2000. Many chemicals were being checked for the first time whereas others had been studied in earlier years too. Personnel carrying out the CDC study travel in a convoy of tractor-trailers collecting blood and urine samples. In this second survey, they collected samples from 2500 adults and children in 20 locations across the country. People in the study were selected to be representative of the entire population in terms of age, gender, race and ethnicity. Box 4.1 summarizes some results. The CDC will continue to collect new samples in upcoming years and continue to test for additional chemicals not yet examined.

Box 4.1 | Chemicals likely to be in your body

The word "metabolite," as used below, refers to a substance produced when living organisms process a chemical and convert it to some other chemical. Among the chemicals the CDC found in the body are the following.

- Cotinine. This is a nicotine metabolite that, if found in blood or urine, indicates exposure to tobacco smoke. Compared with the early 1990s, the body burden of cotinine dropped 75% in adults, probably due to regulations restricting smoking. It dropped only 58% in children: parents are protected from smoke in workplaces, but no regulations apply to smoking at home.
- Twelve hazardous metals. ■ One of these, *lead*, has long been a major children's health concern, and blood levels have been measured for decades. In 1990 (compared to the late 1970s), children's blood levels had dropped significantly (presumably due to banning lead from gasoline and other actions). In 1991 to 1994, only 4.4% of children aged 1 to 5 still had elevated blood lead levels (greater than 10 μg/100 ml). This fell to 2.2% in the current study. Children living in old lead-painted homes are still at risk. ■ The body burden of *cadmium* (also

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[2] US Centers for Disease Control and Prevention. 2003. Second National Report on Human Exposure to Environmental Chemicals. http//www.cdc.gov/exposurereport/ (accessed January, 2003).

previously studied) has remained steady. ■ *Mercury* is of concern because the developing fetus is especially sensitive to this element. It was found in the blood of about 8% of women of childbearing age at above the "precautionary" level of 5.8 ppb. Eating mercury-contaminated fish is the primary source of exposure: large tuna, swordfish, shark, king mackerel, and tile fish. To lower the mercury content of fish, the CDC recommends that society makes more effort to lower mercury emissions from electric power plants, waste incinerators, and chlorine production facilities. ■ *Other hazardous metals* detected included cobalt, tungsten, and uranium.

- Pesticide metabolites. ■ The CDC detected metabolites of *organophosphate pesticides*; this is a concern because although the metabolites detected have short lives in the body, almost everyone tested had them. This means people were exposed shortly before testing, and indicates too that exposures are probably frequent. Children had greater body burdens than adults because they take in more, pound per pound when breathing, eating, and drinking. ■ A metabolite of the *organochlorine pesticide*, DDE (the major metabolite of DDT) had declined compared to pre-1990 levels. This was expected because DDT production was banned in 1973. Nonetheless, even teenagers, people born well after DDT was banned, have small body burdens. And probably because DDT was still manufactured in Mexico until recently, DDE levels were about three times higher in Mexican American immigrants.
- Phthalate metabolites. ■ Seven metabolites of *phthalates* were found in urine. Phthalates are chemicals used in plastic products, such as children's toys, to make them more flexible. They are also used in cosmetics, toiletry items, and industrial solvents. Investigators were surprised because the phthalate metabolites found in the highest amounts did not come from the phthalates used in the highest amounts. One found at higher than expected amounts was *diethyl phthalate* used in soaps, perfumes, and shampoos. The CDC hypothesized that direct skin contact with these products may explain this, absorption across the skin may occur; see discussion of phthalates in Chapter 3.
- Dioxins. CDC was encouraged to see that blood levels of dioxins, furans, and polychlorinated biphenyls (PCBs) were below detection limits for most people. These chemicals were detectable in studies done in the 1980s. The decreased body burdens are probably due to ongoing efforts to reduce emissions of these chemicals into the environment.

Should you be concerned?

Richard J. Jackson, who directs the CDC's National Center for Environmental Health, stated that: "just because a chemical can be measured in blood or urine doesn't mean it causes illness or disease." He did note that the CDC is undertaking dozens of studies to address health concerns that arise because of these body burdens, and to see what levels of certain chemicals are safe or unsafe. It is not enough to know that the chemical is in the body. The CDC wants to know what happens to it within living cells. *Industry* organizations say the levels detected are mostly very low and are unlikely to pose health concerns. *Environmental organizations*, however, express concern and even alarm that so many xenobiotics are in our bodies. Other countries are also planning to do similar studies.

Of what use are these studies?

A CDC official said the results presented, "a giant step forward for us in exposure information and will make big differences in our ability to identify and prevent disease." How? First recognize that not just any chemicals, but chemicals of concern were being measured. ■ For chemicals already studied over many years, the results may be encouraging: levels of the highly toxic dioxins and the metal lead in people's bodies have decreased over time meaning that measures taken to reduce dioxins and lead in the environment are working. ■ On the other hand, the metal mercury, a risk to fetal development, was often present at levels of concern in women of childbearing age. This tells us we need to do more to reduce exposure. ■ What about chemicals never before measured? Results provide us with a baseline against which to compare future body levels. They also tell us about current levels in people so that in the future the CDC can tell if levels have increased or decreased. And if they find levels that are increasing, are these associated with detrimental health effects? ■ For chemicals such as those phthalates found at surprisingly high levels, we can investigate why they are high and if we should take special efforts to reduce them.

SECTION II

Epidemiological studies

Epidemiology is the study of the causes of disease, its distribution in human populations, and the factors influencing the distribution. You saw in Chapter 3 the results of one study: the association made between vaginal cancers in young women with the DES taken by their mothers when they were pregnant with them. Epidemiological studies are important because they look directly at *human* risk. They examine exposure to a chemical or other agent, and look for a connection with adverse health effects.

Historically, epidemiology was used to trace infectious disease outbreaks caused by pathogens (pathogenic microorganisms): for example, when outbreaks of cholera or typhoid fever were traced to a contaminated water supply. It is usually more difficult to link a disease to a chemical exposure. However, in one successful case in 1775 the English physician Percival Pott noted that scrotal cancer was common in boys who worked as chimney sweeps. Observing their intensive exposure to coal dust and tar, especially as they worked without clothing, he correctly recommended that the boys should regularly bathe to remove soot. Before modern workplace safety controls were instituted in industrialized societies, a number of diseases were traced to occupational exposures. *Asbestos* exposure was associated with asbestosis, lung cancer, and mesothelioma. *Benzene* exposure at high levels was associated with blood abnormalities and leukemia. Exposure to *radon* at the high levels found in uranium mines was associated with lung cancer.

Note the word *association* in the preceding sentences. An association is a relationship between two situations. It is not proof that one caused the other. ■ Strong associations. Epidemiologists work to find associations so strong that they might be taken as proof. The cigarette smoking and lung cancer association is too strong to deny. The best epidemiological studies examine large numbers of people, preferably those exposed to high concentrations of the suspect substance. This is how an association between cigarette smoking and lung cancer was made, allowing us to attribute about 30% of all American cancers to tobacco use. Likewise, because so many millions of people drink alcohol, it was possible to link excess drinking to liver cancer. ■ Small populations. Although more difficult, good studies can be done on small populations especially if the adverse effect is unusual and all affected individuals are known to share an exposure in common. One successful linkage involved only about 100 individuals. Each had an uncommon liver cancer, and each had suffered workplace exposure to the chemical vinyl chloride. Another clear link that involved quite small numbers of individuals was the association of vaginal cancer in young women with mothers who took DES.

Difficulties in carrying out epidemiological studies

Confounding factors

One major reason that chemical epidemiological studies can be frustrating is *confounding factors*; these may influence study results independently of the exposure being studied. If a person smokes tobacco or drinks alcohol, this can influence their susceptibility to a disease, quite aside from the exposure being studied; so can gender and age, malnutrition, and a number of other factors.

Exposure

Even more difficult than assessing confounding factors is accurately evaluating exposure to the agent under study. One author of a *Science* article said, “Of all the biases that plague the epidemiological study of risk factors, the most pernicious is the difficulty of assessing exposure to a particular risk factor.” The reason for this is that exposure information typically relies on human memories, which may be both faulty and selective.

Community studies

So-called “community studies” are usually very unsatisfying. These are carried out in communities that may have an excessive rate or *cluster* of a particular disease. Almost any community, by chance, will have excess rates of some diseases, but people often suspect that the disease results from a common exposure, perhaps a drinking-water contaminant, chemicals in a community hazardous-waste site, or air emissions from a manufacturing facility. To follow up on community concerns, epidemiologists must first determine if there is indeed a cluster. This is difficult. For instance, how do they decide on a boundary around the area where the suspect disease occurs? If the cluster appears real, or sometimes even if it does not, epidemiologists look for an exposure shared by the individuals who have the disease. However, the population is usually too small to make successful statistical connections. It's especially difficult to evaluate exposure if individuals know why they are being studied – bias creeps into the study. Nonetheless, community studies continue to be done, demanded by anxious and suspicious residents. Because it is so difficult to reach conclusions in a single community, some investigators are taking a multi-site approach. Results from a number of similar sites are pooled, such as a number of communities with similar hazardous-waste sites. The data are analyzed to see if more definitive results are obtained than for one community alone. These studies too are controversial.

Judging epidemiological studies

Harvard epidemiologist, Professor D. Trichopoulos, observed that epidemiologists can be, "a nuisance to society. People don't take us seriously anymore, and when they do take us seriously, we may unintentionally do more harm than good." This can happen if study results are reported with a fanfare in the news media. It makes it difficult for you, the person receiving the information, to judge how seriously to take it. There are questions you can ask to help you judge a study.

- Is this the first study on this agent, or have there been several studies all showing fairly consistent results? Exposure to very fine particulate matter in the air is a case in which many studies have shown that, as air levels of particulates increase, so do hospital admissions for respiratory diseases and some heart problems.
- How many people were studied – many thousands or just a few hundred? In one case several small studies indicated an association between a high-fat diet and increased breast-cancer risk. But a careful study of 121 000 nurses followed for 20 years showed no association. This respected study largely closed off discussion of an association between fat intake and breast cancer.
- Were confounding variables – such as age, smoking, diet, or other lifestyle factors – considered? In the case just mentioned of the 121 000 nurses, their backgrounds were well known. This allowed correction for confounding factors.
- Is the disease rare? This may allow it to be more easily linked to a risk factor. Was it, for example, an increase in a specific rare cancer or a general increase in all cancers?
- How large was the risk factor? A 30% increase in risk or even a doubling may mean little, especially with only one study. But if there is a three- or four-fold increase in risk, the association carries more weight even with only one study. This is especially so if confounding factors were carefully evaluated.
- However, even for strong associations, we need to show that the relationship is biologically plausible; that is, can results be explained in terms of how living organisms are known to work? As noted above,

studies consistently indicated increased hospital admissions in people exposed to fine particulates, but it was more difficult to come up with a good biological explanation.

- If clinical work on human beings has been done, are the results consistent with the epidemiological study?
- Finally, is the story sensationalized? Even careful studies are often difficult to interpret definitively. Sensationalizing a report may yield only confusion.

Limits of epidemiology

Epidemiology cannot answer all the questions put to it, even when many well-designed studies of one particular risk factor are done. This has been the case with studies of electromagnetic fields (EMFs). Epidemiological studies have searched for connections between human cancer and exposure to EMFs for a quarter of a century. Results obtained are inconsistent, sometimes contradictory. A US National Academy of Sciences panel, after carefully evaluating these studies, reported in 1996 that it found no evidence of adverse effects on animals or cells at EMF levels found in human residences.[3] If EMFs pose a risk at the ordinary levels that people encounter, the risk is very small. However, it is just those possible small risks that pose a major problem for epidemiologists because so many factors could influence study outcomes. And a small risk can be important: hundreds of millions of people use electricity and are exposed to EMFs, so even a small risk could affect many people. This motivates researchers to continue studying EMF risks.

Despite their problems, epidemiological investigations can be tremendously useful and provide information that no other type of study can. Two studies were so highly regarded in the 1990s they resulted in major policy recommendations:

- Epidemiologic studies made an association between excess vitamin A intake during pregnancy and an increased risk of serious birth defects. A second study strongly supported that conclusion: pregnant women taking four times the recommended daily intake of vitamin A much increased their risk of giving birth to babies with cleft lip, cleft palate, and major heart defects. This study led to a recommendation that women of childbearing age should not take vitamin A in amounts exceeding the recommended dose.
- Birth defects were also the subject of another study. In this case the problem was a *lack* of a vitamin – folic acid, a B vitamin – in pregnant women's diets. A lack of folic acid was strongly associated with serious birth defects, spina bifida (in which the spinal cord is not completely encased in bone), and anencephaly (in which a major part of the brain does not develop). The association was so clear that it too led to action: producers of common grain products

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[3] Anon. NAS says EMFs no hazard. *Environmental Health Perspectives*, **105**(1), January, 1997, 25.

such as flour and cereals began adding a folic acid supplement to help ensure that women of childbearing age had a sufficient intake.

Questions 4.2

1. Weigh the pros and cons of a study made to see if there is an association between nitrate levels in drinking water and bladder cancer. In the mid-western US state of Iowa, large amounts of nitrogen fertilizer have been used on agricultural fields for many years. *Nitrate* runoff from these fields has reached the drinking water of many municipalities, and it is present at greater than 5 parts per million (ppm) in many cases. In 2001, researchers at the University of Iowa reported the results of a study on 21 977 women in Iowa.[4] The women studied had drunk from the same water supply for more than 10 years, and only communities where at least 90% of the water supply came from a single source were included in the study. Each woman's nitrate exposure was estimated on the basis of the level in the water she drank. Results were adjusted for confounding factors: smoking, age, education, physical activity, and the amount of fruits and vegetables consumed. Researchers found a statistical link between nitrate in drinking water and an increased risk of bladder cancer. Women who drank water containing more than 2.5 ppm nitrate had a risk factor of 2.8; that is, they were almost three times more likely to develop bladder cancer than women whose drinking water contained less than 0.36 ppm. One author of the study noted that because there were only 47 cases of bladder cancer among the 21 977 women, the association must be considered moderate. However, the authors do believe that the results are biologically plausible as the body can convert nitrate into known carcinogens, *N*-nitroso compounds. The results were of concern because they associated bladder cancer with nitrate levels as low as 2.5 ppm whereas the US EPA standard for nitrate in drinking water is 10 ppm. The 10 ppm standard was set 50 years ago to avoid cases of blue baby syndrome. At the time, possible chronic effects of nitrate, such as cancer, were not considered. Based on these results, some suggested that the EPA should lower its drinking water standard for nitrate. However, other epidemiologists evaluating the study did not believe that the study showed a meaningful association between nitrate, at the levels studied, and bladder cancer. If you had to advise the EPA as to whether it should make its drinking water standard for nitrate more strict, what would you recommend and why?
2. Examine Box 5.5, which reports on the relationship between disease and tiny particulates in the air. (a) In what ways may the results reported be superior to the results given above for nitrate in drinking water? (b) To what extent do the studies fulfill the criteria for having confidence in the results of epidemiological studies?
3. Consider Box 3.4. Describe a pathway that could account for cow's milk becoming contaminated with I^{131} after the 1986 Chernobyl nuclear plant explosion.

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[4] Kristen, K. Nitrates linked to bladder cancer. *Environmental Science and Technology*, **35**(13), 1 July, 2001, 279A–280A.

4. Studies show that about 60 of about 4000 substances in tobacco smoke are carcinogens in laboratory animals. These include tar, nicotine, formaldehyde, and benzene. In humans, 24 of 30 epidemiological studies support the conclusion that non-smokers exposed to secondhand smoke have a greater lung-cancer risk than do unexposed people. (Secondhand smoke is the side-stream smoke emitted between puffs of a cigarette plus the smoke exhaled by the smoker.) (a) Do results such as these indicate to you that secondhand smoke is a cancer risk? Explain. (b) What circumstances might increase the risk of developing cancer as a result of exposure to secondhand smoke?
5. American farmers have higher rates of the cancer, non-Hodgkin's lymphoma as compared with the general population. Environmental factors may contribute to these rates. Think about the lifestyle of farmers. What environmental exposures *other* than pesticides, whether they be chemical or non-chemical, might contribute to their increased cancer rate?

SECTION III

Chemical risk assessment

Risk is defined as the probability of suffering harm from a hazard. A *hazard* is the source of the risk – not the risk itself. For a hazard to pose a risk to you, you must be exposed to it. ■ To help you make the distinction, look at Questions 3.1, which compared lead at Smuggler Mountain with lead in peeling paint in old houses. Lead is the hazard in both cases, but its risk differs in the two situations. ■ Similarly, think about walking into a cotton field sprayed with a hazardous insecticide. Your exposure to the insecticide, and your risk, differs if the field was sprayed 1 hour previously as compared to 24 hours previously. ■ The word hazard goes beyond chemical hazards: infectious disease organisms, pathogens, are biological hazards; ionizing radiation or hot water are examples of physical hazards. Chemical risk assessment is a process that systematically examines the nature and magnitude of a risk. A risk has a probability ranging from zero to one. Zero indicates no risk at all, and one indicates definite harm.

Why do we do chemical risk assessments?

Risk assessment provides answers to questions such as: What is the risk to my child's health of drinking water containing 3 ppb of atrazine (an herbicide)? What is my risk if I eat meat containing 1 part per billion of benzopyrene (a carcinogen)? What is the risk to a worker who is breathing air containing 1 part per million of benzene (a carcinogen)? How much dioxin (a carcinogen) can safely be left in the soil of a hazardous-waste site when it is cleaned up? What should be the standard (the limit) for ozone in city air? What should be the standard for arsenic in drinking water? The results of chemical risk assessment can be used in more complex situations too. However, the chemicals are ordinarily still evaluated one at a time.

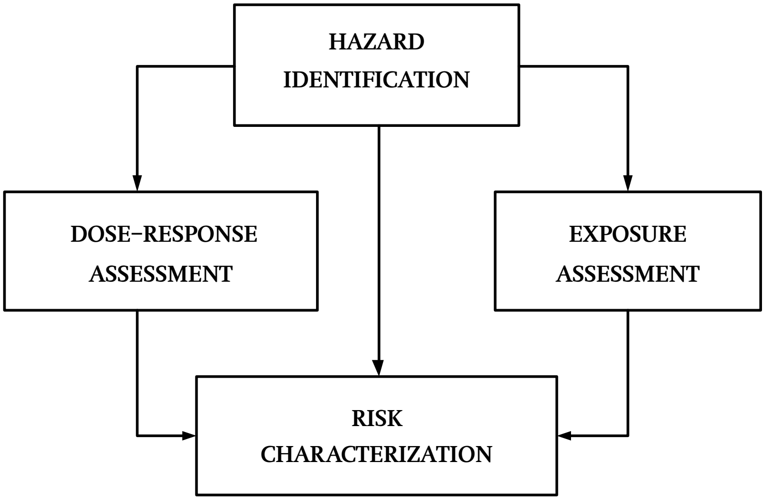
■ In Chapter 2 you read of comparative risk assessment, comparing one environmental risk to another, for example when we ask, What is the risk of stratospheric-ozone depletion as compared with the risk of acid rain? Many environmental risks, such as ozone depletion and acid rain, also involve chemicals, so chemical risk assessment is important in comparative risk assessment too. ■ Another situation where chemical risk assessment is valuable is in analyzing the risks of hazardous-waste sites. However, such sites often have too many chemicals to evaluate each chemical individually. Instead, investigators determine which chemicals are present and in what amounts. Then they do risk assessments on *indicator chemicals*, those believed to pose the greatest risk to nearby populations.

But whether we are looking at a hazardous-waste site or a contaminant in air or water, how do we decide when a risk assessment is warranted? First, we must answer the question: Is there exposure to the chemical? If there is no exposure, there is no risk to humans, plants or animals. If there is exposure, then the chemicals of most concern are those that are very toxic or to which we have high exposure. Some chemicals on which risk assessments are often done are as follows. ■ A pesticide's purpose is to kill, and it may harm species other than those it was intended to kill; so we do a risk assessment on any new pesticide. ■ Food additives will be ingested, so exposure will definitely occur. A risk assessment is therefore carried out on new additives. ■ There are many chemicals that we already use and are already exposed to, but whose risk has not been systematically studied. More and more people want these chemicals subjected to risk assessments too.

Risk assessment is a powerful tool, and the answers it provides are indeed important. However, as you study the section below, notice that risk assessment is not, and cannot be, precise because we very seldom have enough information. Indeed, risk assessment *helps to compensate for a lack of information*. As a US Occupational Safety and Health Agency official stated, "People need to understand that we do risk assessment because we don't have conclusive scientific evidence available. Risk assessment is not science; it is a set of decision tools to help us make informed decisions in the absence of definitive scientific information." That is to say, the tools of risk assessment can help us evaluate environmental risks and set priorities among them, but they do not provide definitive answers.

Health effects evaluated by chemical risk assessment are in two categories. One is *non-cancer health effects*; that is, any and all adverse effects other than cancer. The second is *cancer*. Both cases involve four steps (Figure 4.1). Be attentive to the differences between assessments done on chemicals not suspected of being carcinogens as compared with those suspected of being carcinogens.

Figure 4.1 The four steps of chemical risk assessment



Non-cancer risk assessment

There are four steps in the risk assessment of a chemical (Figure 4.1).

1. First is a *hazard assessment*, why is this chemical considered a hazard?
2. Calculate *exposure* to the chemical.
3. *Dose–response assessment*, this examines what doses are toxic to laboratory animals.
4. The final step, *risk characterization*, takes all the information from steps 1 to 3 and calculates a dose of the chemical that is safe for human exposure.

Step 1. Hazard identification

The first question is how is this chemical hazardous? To do this *hazard identification* step we collect and analyze information available on the chemical, examining research literature, government-agency profiles, and other information sources. Just some of the questions needing to be answered follow. ■ What toxic effects does it cause in laboratory animals? Does it, for example, harm the nervous system, interfere with respiration, cause birth defects, or suppress the immune system? How does it affect animals and plants? ■ How does exposure occur: by skin absorption, by ingestion, or by inhalation? Answers to these and many other questions relating to the chemical are answered to the extent possible.

Step 2. Dose–response assessment

- Find a dose safe to laboratory animals. Expose different groups of animals to increasing doses of the chemical. Observe the response to each dose over days, weeks, or months. ■ A control group does not receive the test chemical. ■ A second group receives a low dose.

■ A third group receives a larger dose. ■ A fourth group receives a yet larger dose.

- The highest dose that animals tolerate without showing ill-effect is the "no observed adverse effect level" (NOAEL); see Figure 3.1. But, what we really want to determine is a dose that is safe to humans exposed to it, even if exposure occurs over a lifetime. So, we divide the NOAEL by a *safety factor*.
- Determine a safety factor. To do this, assume the average person is 10 times more sensitive than test animals. ■ Also, assume some humans are 10 times more sensitive than the least-sensitive humans. This means multiplying 10 by 10 to yield a safety factor of 100. ■ If the animal dose–response study is not of high quality, introduce another multiple of 10 to increase the safety factor to 1000. Even if the data are of good quality, consider if children are exposed to the chemical. If they are, increase the safety factor even further (see Box 4.2).
- Determine the reference dose. Divide NOAEL by the safety factor. This gives the *reference dose* (RfD). The reference dose is one considered safe for humans over a lifetime of exposure. The smaller the RfD, the more toxic the chemical.
- Example: What is the RfD of a chemical with a NOAEL in rats of 1 mg/kg per day (1 milligram per kilogram of animal body weight per day)? Assume that the animal data are good, and divide 1 mg/kg per day by 100. This yields an RfD of 0.01 mg/kg per day. (The RfD is sometimes also called the *acceptable daily intake,* ADI.)

Box 4.2

Why use factors of 10?

In the 1930s the first antibiotic drugs, the sulfonamides, came into use. In 1937, a US drug company found that it could dissolve sulfonamides in a sweet-tasting organic chemical, *diethylene glycol,* an antifreeze. The sweet taste made it attractive to children. The drug company sold this elixir of sulfonamide–diethylene glycol without first testing its toxicity in animals. Subsequently, about 120 people around the United States died, many of them children. This event led directly, in 1938, to the passing of an amended Federal Food Drug and Cosmetics Act (FFDCA) to assure that such a tragedy would not occur again.

After discovering the illnesses and deaths, US Food and Drug Administration personnel traveled the country by train collecting information on the amount of diethylene glycol that each affected individual drank. From this information, agency personnel calculated an approximate LD_{50} for human beings – the dose killing about half of the people exposed to it. They observed about a ten-fold variation in human sensitivity to the chemical. Returning to their laboratories, they tested the toxicity of diethylene glycol in animals. They found that animals too had about a ten-fold variation in sensitivity. Beginning at this time the FDA began the practice of dividing a chemical's NOAEL by 100 (10 × 10) to provide what they believed to be a margin of safety for humans: humans should not be exposed to more than a hundredth of the dose that shows no adverse effects in animals. In recent years, if good information on a particular chemical is available, the US EPA determines a safety factor more specific to that chemical, which may be greater than or less than 100. However, in 1996 after the US Congress passed the Food Quality Protection Act, another factor of 10 was introduced for chemicals to which children are exposed, especially pesticides. This means dividing the NOAEL by 1000 (at least) to obtain a safe dose.

Although the elixir of sulfonamide provided a dreadful lesson, not everyone learned it. In the 1990s, a Chinese company shipped medicinal glycerin syrup to Haiti – it contained diethylene glycol. Eighty-six Haitian children who consumed the syrup died of kidney failure.

Step 3. Exposure assessment

What is the human exposure level to the chemical? Wild animals or an entire ecosystem may also be exposed to the chemical, but here we will consider only humans.

- Source. What are the sources of the chemical? Is it emitted to air or water from an industrial facility? Is it emitted in motor-vehicle exhaust? Is it leaching from a waste dump into groundwater?
- Route of exposure. How does exposure occur? ■ Is it through drinking water? If so, what is its water concentration, and how much does an average person drink? ■ Is it through food? If so, which foods? What is the concentration in each food, and how much of each is eaten? ■ Is it through soil? If so, what is its concentration in soil, and how much soil is ingested or inhaled (as dust)? ■ Is it through air? If so, what is its concentration in air, and how much is inhaled? ■ In all these cases, for how long does exposure continue?
- Most highly exposed population. ■ Some Native Americans eat large amounts of fish, and have high exposure to chemicals that concentrate in fish such as PCBs or methylmercury. ■ Children are most likely to ingest soil, and are at special risk from soil contaminants. ■ Small children living in houses with deteriorated lead paint have high lead exposures. ■ Urban dwellers may have the highest exposure to motor-vehicle exhaust. ■ Urban people drinking chlorinated water are most likely to have the highest exposure to *disinfection byproducts*. ■ Rural people who drink well water may be more exposed to radon, nitrate, and arsenic. ■ Individuals living near a hazardous-waste site are more likely to have exposures to chemicals emanating from that site.
- Children. Give special consideration to children's exposure.
- Worst-case assumptions. There is seldom enough information for a good evaluation of exposure. To compensate, we often use *worst-case assumptions* meaning, what is the highest possible exposure that could occur in the circumstances? Lacking better information, answers to worst-case assumptions are used.

Step 4. Risk characterization

Risk characterization brings together everything we have learned about the chemical, its hazards, it dose–response toxicity, and exposure to it. This information is used to calculate its risk, its *hazard quotient*. ■ If more than one chemical is being evaluated (as when evaluating several chemicals at a hazardous-waste site) the hazard quotients are added together to yield a higher risk. ■ If there are multiple pathways of exposure to a chemical (food and water for example) these are added together to yield a higher risk. ■ Remember from dose–response studies that an RfD is the dose considered safe over a lifetime of exposure. So, if a chemical's hazard quotient is less than its RfD, it is not considered a risk (see Box 4.3).

Box 4.3 A giant risk assessment

The US 1996 Food Quality Protection Act (FQPA) required the US EPA to carry out several actions. ■ It had to review all its current tolerances for 470 pesticides (many of which have more than one tolerance level depending on the particular food).[5] All together the EPA had to review 9700 tolerances set in earlier years. ■ The EPA was instructed to determine not just the risks of one pesticide at a time, but to determine the *cumulative risk* from all pesticides that shared a common mechanism of toxicity. Thirty organophosphate pesticides and 12 carbamate pesticides share a common mode of toxicity. Adding all these risks together was expected to yield a higher risk than any calculated in the past. ■ The EPA also needed to consider *all possible routes of exposure* not just exposure from food, but also drinking water, and any indoor uses. ■ And, when it sets new tolerance levels, the EPA was instructed to pay particular attention to children. Without compelling evidence that children are protected, the EPA must apply an additional ten-fold safety factor.

These determinations posed a gigantic task and the EPA's job, to be completed by 2006, is not yet done. To better analyze so many factors, the EPA developed a risk-assessment model that accounted for exposures from food, water, and residential usages. Manufacturers of organophosphate pesticides had been very concerned that the cumulative risk approach would endanger the use of many of their products. However, in 2002, after assessing 1000 tolerance levels for 30 organophosphate pesticides, the EPA reported that 28 of the 30 were safe. The other two, dichlorvos and dimethoate, were linked to health problems and may be banned or their use limited. The EPA also reported that drinking water was insignificantly contaminated with these pesticides.

Human subjects

Years ago human volunteers were used in chemical testing, a practice discontinued because of ethical concerns. However, pesticide manufacturers recently did 15 studies using paid adult human volunteers. The volunteers ingested doses of

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[5] The EPA's definition of a pesticide tolerance is: "The amount of pesticide residue allowed by law to remain in or on a harvested crop. The EPA sets these levels well below the point where the compounds might be harmful to consumers."

pesticides expected to be below a human NOAEL. The reason companies performed human tests was that they hoped to prove their safety in humans at the doses used. Knowing this information for humans would allow one factor of 10 – the one used to account for differences between humans and animals – to be dropped. This would lead to higher RfD values for pesticides if humans were less sensitive than test animals. Manufacturers point out that the human tests they do are similar to those done when testing the toxicity of a new pharmaceutical. The EPA was greatly concerned about whether to allow the use of human data and sought guidance. However, the EPA will probably have completed its huge re-evaluation of pesticide tolerances before ethical issues have been resolved, so the issue may be moot for the foreseeable future.

Cancer risk assessment

To do a risk assessment on a chemical suspected to cause cancer takes 4 to 6 years, and costs several million dollars. These factors limit the number of chemicals tested. Only a chemical for which there are strong reasons to suspect that it is a carcinogen will be tested. Only about 500 chemicals have been so evaluated.

Step 1. Hazard identification for possible carcinogens

Hazard identification is particularly important when considering a possible carcinogen. What are the reasons for suspecting the chemical is a carcinogen? For instance, is it chemically similar to a chemical known to be a carcinogen? What do laboratory animal studies that have already been done with this chemical show? Is there epidemiological information on the chemical that might support such a suspicion? Other important questions are: Is the chemical produced in large quantities? Are large numbers of people exposed to it? Yes answers to these questions may justify a costly long-term study. However, if the chemical is produced only in small amounts or is only used by researchers under carefully controlled conditions, it probably won't be tested.

In an earlier era, when safety controls were poor in industrialized countries, evidence that a chemical was a carcinogen was sometimes found in the workplace. ■ Benzene, a widely used industrial chemical, was found to be associated with the risk of leukemia and aplastic anemia. In this case, animal studies – indicating that benzene was a carcinogen – were not done until later. ■ Vinyl chloride and asbestos are other chemicals whose ability to cause cancer was first observed in humans in the workplace. ■ Today, the intent is to know a new chemical's hazards before using it. If it is dangerous, a society may choose to eliminate its use entirely. Or, if no substitute is available, it may be used under carefully controlled conditions. Unfortunately, in the poorly protected workplaces of impoverished countries this often does not happen.

Step 2. Exposure assessment for possible carcinogens

Exposure is evaluated in the same way as described above for chemicals not suspected of being carcinogens.

Step 3. Dose–response assessment for possible carcinogens

The US National Toxicology Program recommends a special protocol for cancer dose–response studies. Rats and mice are typically the test species. In exceptional cases, as for a potent carcinogen such as 2,3,7,8-TCDD, additional species are tested too. Exposure begins immediately after weaning test animals. The suspect chemical is administered to each animal every day for 18 months to 2 years (lifetime studies).[6]

1. A control group receives no test chemical.
2. A second group receives the *maximum tolerated dose* (MTD). An MTD is the highest dose that does not reduce the animals' survival as a result of causes other than cancer. The MTD is determined using studies similar to those used to test chemicals that do not cause cancer, except that the studies last for longer periods of time.
3. A third test group receives one-half of the MTD.
4. A fourth group, receiving a lower dose, is often included.

Some control animals will also develop tumors over a lifetime. This means that toxicologists look for *excess tumors* in the animals receiving the suspected carcinogen.[7] Look back at Figure 3.1 and see that, for chemicals that are not carcinogens there are low-dose levels where no adverse response occurs, the NOAEL. Now look at Figure 4.2. As a means of being cautious (conservative) an assumption is made: *any dose of a carcinogen greater than zero* is assumed to pose some risk; that is, the straight-line relationship (seen in the upper part of the line with the asterisks) goes all the way to zero. It is assumed that there is no NOAEL. But notice too the rectangle with the question mark – the chemical is not actually tested at the low-dose levels covered by the rectangle. Even assuming that there is no safe dose, there is ordinarily a dose–response relationship; that is, at a higher dose, more cancers are observed. Moreover, people are not typically exposed to doses anywhere near as high as the MTD. They may be exposed to doses that are hundreds, thousands, or hundreds-of-thousands of times lower than doses tested in animals (see Box 4.4).

If significantly more tumors are seen in the test groups as compared with controls, a *cancer potency factor* is calculated (Table 4.1). The higher the cancer potency factor, the more potent is the carcinogen. Chemicals display huge differences in their potency, in

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[6] If possible, the chemical is added to food. If animals will not accept it in food, it is given through a stomach tube (a process called "gavage"). If the chemical is an airborne one, animals are exposed to it in an enclosed chamber 5 days a week for 6 hours each day. The doses administered are calculated as milligrams per kilogram of body weight (mg/kg). Each dose is tested in each species, 50 males and 50 females, so 100 animals for each dose.

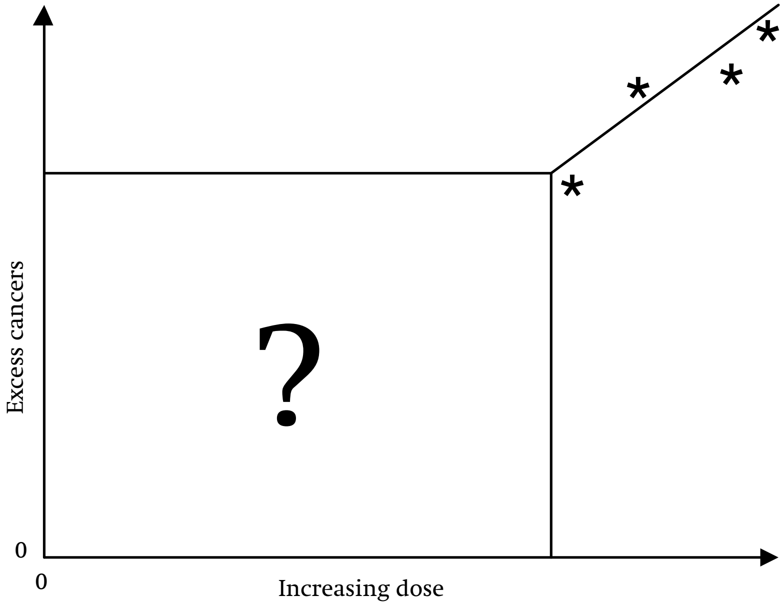
[7] Researchers also look for unusual cancers or types of cancers not seen in control animals. Both benign and malignant tumors are counted.

Table 4.1 Cancer potency of selected chemicals

Chemical	Cancer potency factor[a]	Chemical	Cancer potency factor[a]
2,3,7,8-TCDD	100 000	PCBs	4.34
Aflatoxin B_1	2900	Nickel	1.05
Ethylene dibromide	41	DDT	0.34
Arsenic	15	Chloroform	0.081
Benzo[*a*]pyrene	5.8	Benzene	0.029
Cadmium	6.1	Methylene chloride	0.014

[a] Expressed as mg/kg per day.

Figure 4.2 Excess cancers with increasing dose of a carcinogen



their ability to cause cancer. "Dioxin" (2,3,7,8-TCDD), the most potent rodent carcinogen known, is 10 million times stronger than the weakest carcinogen. Aflatoxin B_1, a mold toxin, is also potent although considerably weaker than TCDD. In turn, aflatoxin is 8500 times more potent than DDT. Chloroform, benzene, and methylene chloride are examples of weak carcinogens.

Step 4. Risk characterization for possible carcinogens

At this point, the chemical's hazard identification studies are done, as are the exposure studies. Cancer potency calculations resulting from dose–response studies are completed too. Now, taking all these studies into account, further calculations are done, and a risk statement is prepared on the probability that a given exposure will result in cancer. Risk is expressed as the increased chance – due to the exposure – of developing cancer over a 70 year lifetime. Illustrations, using drinking-water contaminants as examples, follow. ■ Arsenic. For every 2 additional μg/l of arsenic in drinking water, risk increases by one in 100 000. That is, for every 100 000 people, one additional case of cancer is projected. ■ Tetrachloroethylene. For every 2.4 additional μg/l of tetrachloroethylene, risk increases by one in a million. ■ Radon. Consider a specific level of contamination: for drinking water containing 300 picoCuries/liter (pCi/l) of radon, the increased cancer risk is two in 10 000. The numbers just given for these three contaminants are specific, but no one really knows the exact risk. In fact, US regulatory agencies routinely add a caveat to their assessments: "These estimates represent an upper bound of the plausible risk and are not likely to underestimate the risk. The actual risk may be lower, and in some cases, zero." (See Box 4.4.) In other words, a risk assessment produces a theoretical number. Compare a theoretical risk to a known risk such as driving. Each year about 40 000 Americans are killed in driving accidents. Given this number an accurate calculation can be made as to the risk of death that each person faces when driving.

SECTION IV

Risk management

Up to this point scientists have done the work, including the risk characterization. Now, they hand over their results to non-scientists, risk managers. It is the risk managers who decide how to lower risk. Risk managers often work in regulatory agencies such as the Environmental Protection Agencies or the World Health Organization. Or, they may be law makers, legislators. The major factor in managing risk is to reduce the risk. However, other factors must be considered. ■ Statutory requirements: what does the law require? ■ Technology: is the technology available to control the pollutant in question? ■ Cost: the cost of risk reduction is always a factor. ■ Public concerns: an aroused public can push risk reduction measures. ■ Political concerns: politics affect decision making.

Box 4.4 | Making assumptions

To calculate the cancer risk resulting from exposure to a chemical, assumptions are made. It is assumed that: (1) A chemical that causes cancer in animals, can also cause cancer in humans. (2) It is legitimate to extrapolate from the high doses used in animal studies to the ordinarily very much lower doses to which humans are exposed. (3) All carcinogens are initiators (Table 3.6) although it is known that some are promoters. (4) A chemical is a carcinogen even if it promotes tumors only at MTD, or if there are excess tumors only in one sex, one species, or one strain of that species. In fact, rodent strains prone to develop cancer are often deliberately used. Trichloroethylene was classified as a carcinogen because, given at MTD to a strain of cancer-prone mice, the males showed excess tumors.

Such assumptions make risk estimates more protective. Regulatory agencies want to err on the safe side. A US FDA administrator said, "When science fails to provide solutions, the FDA applies conservative assumptions to ensure that its decisions will not adversely affect the public health." However, countries such as the United Kingdom, Denmark, and the Netherlands believe that there are safe doses (thresholds) of carcinogens. They believe that the dose–response curve has the shape seen in Figure 3.1, not the straight-line response going to zero as seen in Figure 4.2.

The goal of risk managers is to make the risk of a carcinogen *negligible*. An excess cancer risk of one in a million is considered negligible (virtually safe dose, or *de minimis*). A former FDA commissioner stated, "When the FDA uses the risk level of one in a million, it is confident that the risk to humans is virtually non-existent." Some believe that considering how conservative cancer risk assessment is, an excess risk of one in 100 000 or 10 000 is acceptable, especially if the chemical has been shown to be a carcinogen only in animals. Others are less sure.

Risk-management tools

There are often many ways to lower a risk although not all will be feasible or cost-effective. Although laws and regulations are often the first possibility considered, there are usually a number of ways to lower risk.

Laws and regulations

Especially after Earth Day in 1970, laws were passed in many countries mandating reductions in many pollutant emissions. Not just federal, but state and provincial laws too are important in reducing emissions. Most regulations depend on facilities capturing a pollutant end-of-pipe. ■ Other legislative tools are also sometimes used to lower emissions. *Emissions trading* is one. In this process a facility that, for whatever reason, cannot or does not want to reduce its emissions, buys emission rights from a facility that has reduced its own emissions. So, one facility saves money. Although it pays the facility that did make reductions, it costs less than installing the necessary technology. The other facility makes money by selling a portion of its emission rights. ■ Some countries, especially in the European Union (EU), have enacted take-back laws mandating that producers take back products such as cars and computers so these don't pollute at the end of their useful lives (Chapter 18).

Non-regulatory tools

The possibilities outlined below are only some of the approaches used to reduce a risk.

- Educate the public. Inform people as to how they can reduce the amount of radon in their home, or how to safely use chemical products such as pesticides.
- Government and industry working together can foster emissions reductions. ■ EU governments often work with industry, and develop agreements to foster reductions. ■ In some US states, environmental agencies collaborate with industry to find cost-effective ways to reduce emissions.
- Urge industry to voluntarily take action. ■ In the 1990s, a US EPA program enrolled 1150 companies in a program in which they voluntarily reduced emissions of 17 especially risky chemicals by at least 50%. In the early 2000s, many are voluntarily engaged in reducing energy-related emissions. An industry may find that pollution prevention, P^2, saves money. If there is no pollutant, it does not have to spend money capturing or treating the pollutant, or landfilling waste according to expensive rules. ■ Another approach is developing safer chemicals, producing chemicals that pose fewer or no environmental problems. Industry, government, and university researchers are all involved in this effort. ■ Develop "environmentally preferable" consumer products that pollute much less. An example is hybrid cars that use much less gasoline and thus pollute less.
- Non-governmental organizations such as environmental organizations often exert pressure on industry to reduce emissions or become better environmental stewards.
- If we think of risk reduction in the long term, the list of ways to reduce risk becomes longer. Society can choose, for example, to support research in industry, government, or universities aimed at a better understanding of the risk and finding improved ways of reducing it. Or incremental changes can be made, which don't immediately greatly reduce the risk, but can over time and in a cost-effective way make a major difference.

Information as a risk-management tool

Effective risk management requires as much information as possible. Ongoing monitoring of emissions of specific chemicals illustrates one way to gather information. Continuing to gather information on the chemicals themselves is equally important. Information gleaned may be fed back into the hazard identification step, or may help in developing environmental policy. Other ways to gather information follow. ■ After a challenge from the EPA, about 500 US companies in 2002 are voluntarily evaluating the risk of thousands of chemicals for which too little toxicity and environmental impact data were known. They are evaluating 2800 high production volume chemicals (those manufactured or imported into the United States in amounts of more than 1 million lbs (450 000 kg) a year). High-production chemicals are of special interest because, if a chemical is used in large quantities, it increases the likelihood that it can escape into the environment or give rise to human exposure. ■ In a plan that goes beyond the US one, the European Union is likewise studying high-production chemicals. It will mandate that industry demonstrates the safety of their chemical products. Any substance posing a "very high concern" will be phased out of production, although exceptions will be made for essential chemicals that lack better alternatives. In these cases, products containing the chemical would be clearly labeled, thus allowing consumers to decide whether they still want to buy the product. ■ Another testing program, a cooperative effort among US, Japanese, and European scientists, is evaluating not just high-production chemicals, but all 87 000 chemicals in commerce. The goal is to determine which might be acting as environmental hormones. ■ Many countries continue laboratory and field research to glean information on chemicals, how they work, their toxicity, and their environmental impact. Research directed at developing better environmental technologies to control or reduce emissions is also ongoing.

Reducing risk to children

Remember that babies and children are at higher risk from chemicals than adults. Ongoing efforts aim to reduce that risk. ■ In 1996, the US Congress passed the Food Quality Protection Act (FQPA). This requires the EPA to develop new standards for pesticide residues on food. The emphasis is on reducing risk to children. Before the FQPA, cancer risk was the only adverse effect considered when setting a pesticide tolerance (the pesticide residue legally allowed to remain on a food) and no special consideration was given to children. Now the EPA must consider a broad range of health effects not just cancer, particularly those that could affect children. And when setting pesticide tolerances, lacking evidence to the contrary, an extra tenfold safety factor must be added to protect children (see Box 4.3). ■ The EU testing program mentioned above will likewise lower the safety threshold to account for the special sensitivities of the fetus and the young child. ■ The US EPA, citing the special risk that mercury poses to the fetus and small child, announced that coal-burning electric power plants will be required to reduce mercury emissions. ■ In yet another voluntary US testing program, chemical companies are evaluating the health effects of 20 chemicals to which children are likely to be exposed, including acetone, benzene, toluene, and decane. As a follow-up, 20 additional chemicals will be evaluated. ■ More and more programs are directed toward educating parents on how better to protect their children from chemical risks in the home.

Risks to wildlife and natural resources

Because chemical exposure impacts upon the natural world too, chemical risk assessment is also used to examine risks to natural resources: animals or plants, whole ecosystems, resources such as lakes, or stratospheric ozone. Many chemical risks have been identified. A few follow. ■ Effects attributed to DDT in the 1960s included the thinning of bird eggshells (eggs were crushed before they could hatch) and other adverse effects on bird reproduction. ■ Acid rain impacts upon aquatic creatures and damages forests. ■ Chlorofluorocarbons reduce stratospheric ozone leading to increased ultraviolet radiation reaching the Earth. ■ Phosphorus- and nitrogen-containing substances often cause abnormal algal growth in water bodies, leading to too little oxygen for aquatic animals. ■ Polluted runoff flows into water bodies damaging aquatic plants and animals. ■ Industrial discharges damage water life, e.g., the effluent from some paper-mill or municipal wastewater-treatment plants impairs the reproductive development of downstream fish.

Questions 4.3

1. In a mid-west US state, the herbicide atrazine was discovered in drinking water at possibly unhealthy levels in many places. Farmers commonly use atrazine in large amounts, and it reaches surface water by rainwater runoff. What are two ways of reducing this risk? Consider possible farmer, municipal, personal, state and federal actions.
2. Answer question 1 again for a different situation: assume that atrazine was not found in drinking water, but in local ponds and wetlands. Research has indicated that it may be responsible for serious developmental abnormalities in frogs.
3. (a) You live near a large industrial facility that uses trichloroethylene and this organic solvent has been found in your drinking water. How could the solvent have reached your drinking water? (b) You have been told that this level of atrazine is not unhealthy, but you want action. What might you do?
4. The most toxic form of dioxin (2,3,7,8-TCDD) is found in tiny quantities in meat that you buy at the grocery store, especially in fatty hamburger meat. Assume you buy hamburgers anyway. (a) What type of hamburger might you choose in order to avoid most of the dioxin? (b) Once the hamburger is purchased, what steps could you take to reduce your exposure? (c) Is there anything you could do to reduce exposure if you buy hamburgers at fast-food restaurants?

Reducing risks to wildlife

Wildlife is much more poorly protected by laws than are humans. However, there are some protections. In the United States, many facilities discharging into receiving streams must routinely test the toxicity of their effluents to demonstrate that aquatic life is not being harmed. Or, when hazardous-waste sites are cleaned up, they must be cleaned to limits that include protecting surrounding wildlife. In addition, sometimes regulations that protect humans also protect wildlife, for example, when regulations limiting air emissions not only reduce human exposure, but animal, tree, and plant exposure as well. But wildlife is often left vulnerable. Fish and other aquatic life live in, and many creatures drink from, water bodies that do not meet drinking-water standards. On land, the soil in which worms and other vital organisms live is often contaminated. In many countries, human beings too lack protection. One instance (Chapter 3) is the Yaqui Indian children exposed to damaging levels of pesticides. There are many others.

Risks in impoverished countries

"It is a truism in all the world that the major predictor of ill health is poverty because poor people are the least able to obtain uncontaminated water and food . . . and obtain the knowledge necessary to avoid [contamination]."

- Sewage. Pollution of water and food with infectious agents in impoverished countries is typically more serious than chemical contamination. Children under 5 years old are particularly vulnerable. Infection leads to diarrhea, which untreated often leads to death. In Asia alone an estimated 4 million infants and small children die each year from diarrhea. An obvious cause is untreated sewage running directly into rivers and streams – and in roadside gullies – often also used for drinking and washing. More than one billion people worldwide do not have access to clean drinking water.
- Chemical pollutants. Children living in impoverished countries are also heavily exposed to chemical pollution such as that found in motor-vehicle exhaust. The high pollution levels often found can suppress children's immune systems, and they become even more susceptible to infectious diseases.
- Occupational exposure. Children and adults often labor in risky occupations. Two examples are scavenging among trash in dumps and working unprotected in battery-recycling operations where they are exposed to lead fumes when the batteries are melted. Whole families often live at or near work sites, so all are exposed.

Can the risk-assessment and management tools developed in wealthy countries, and often focusing on healthy young adult males, have meaning in such conditions? Pollution-limiting laws may be on the books, but lack of resources and corrupt officials prevent enforcement in many cases. Some governments lack environmental standards although standards relevant to human health are set as guidelines by the World Health Organization. Officials may see environmental protections as a "Western agenda" not relevant to them. Sometimes there is suspicion that such protections will lower economic opportunity for their citizens. Public officials who care about the laws of their countries may lack resources to enforce them, or lack the education to use the laws knowledgeably. Workers and others may accept dangerous exposures as just the way life is. But when the will exists, effective risk-management tools can be developed and enforced even in very poor countries. Just one example is increasing fuel efficiency standards in large cities. These can lower pollution and lower fuel costs as well. Other examples will be seen in later chapters.

Back to the first world

Pointing to conditions in third-world countries is easy. However, high first-world exposures still occur too. Nitrogen oxides (NO_x) pollution resulting from emissions from heavy motor-vehicle traffic in New York, Paris, Tokyo, and Los Angeles is among the highest in the world. Particulate pollution from motor vehicles leading to respiratory infections, is also often high in American and European cities. Environmental justice issues continue in first-world countries: this happens when dumps and other polluting facilities that more wealthy citizens avoid, disproportionately locate in neighborhoods occupied by the poor, or people of color. Roxbury, an inner-city neighborhood in Boston, Massachusetts has within its borders: 80 vehicle repair shops in an area of 1.5 square miles (3.9 km^2), trash transfer stations, heavy-duty truck traffic (often idling as the trucks wait to take on or drop off materials), food-processing facilities with bad odors, furniture-stripping sites, pervasive dust arising from many sources, hazardous-waste sites, and many houses with leaded paint.

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Chapter 5

Air pollution

> "Our world civilization and its global economy are based on beliefs incompatible with enduring habitation of the earth: that everything has been put on earth for our use, that resources not used to meet our needs are wasted and that resources are unlimited."
>
> *Carl McDaniel and John Gowdy*

The reality of outdoor air pollution is more than the words "ambient air pollution" can convey (see Box 5.1). It is the eye-stinging pollution surrounding us in a city crowded with motor vehicles, the odor of ozone on a hot hazy day, the choking dust of a heavy dust storm, the smoke coming from wood or coal fires on a winter day, the fumes from an uncontrolled industrial facility, odor from uncontrolled sewage or an open dump. Many living in wealthy countries are spared the worst of these. Not so for the multitudes living in less-developed countries, who are exposed to these and more; see Table 5.1.

In Chapter 5, **Section I** examines six major air pollutants, which along with volatile organic chemicals (VOCs) account for 98% of US air pollution and similar percentages worldwide. **Section II** introduces the hazardous air pollutants (HAPs), also called toxic air pollutants. **Section III** describes massive pollution that can be directly observed or detected from space while sometimes wreaking havoc at ground level – traveling combustion pollutants, major dust storms, and smoke from mammoth fires. **Section IV** briefly surveys pollution in less-developed countries. Reducing air pollution is a topic in each section. To gain the most from this chapter, it is important initially to learn the criteria air pollutants and their characteristics, and examples of both VOCs and HAPs.

Box 5.1

- Ambient air pollution. This is the pollution in the air around us. It is ground-level, tropospheric air pollution. The troposphere is the lower layer of the atmosphere, which starts at the earth's surface.
- Criteria air pollutants. The term "criteria air pollutants" originated with the US 1970 Clean Air Act. That law required the EPA to set standards to protect human health and welfare from hazardous air pollutants in ambient air. Before setting standards, the EPA had to identify the most serious pollutants. To do so it used *criteria* (characteristics of pollutants, and their potential health and welfare effects). The six pollutants so identified account for the large majority of air pollution in the United States and worldwide. They are: carbon monoxide (CO), ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). Lead (Pb), the sixth criteria pollutant, was included at a time when it was emitted in especially risky amounts.
- Volatile organic pollutants (VOCs). As a group the VOCs, which are also emitted in large amounts, are sometimes considered along with criteria pollutants. They also include major precursors of nitrogen oxides.

SECTION I

Criteria air pollutants

Remember that the higher the dose of a substance to which a living creature is exposed the greater is the possibility of an adverse effect. Now, apply this principle to criteria air pollutants. They are produced in large amounts, and we – and other living creatures – are often exposed at levels high enough to exert adverse effects. Air pollution in Houston, Mexico City, Istanbul, and many other cities, often causes painful breathing, eye irritation, and headaches. Chronic effects also occur, and trees and plants are also adversely affected. ■ Combustion, especially fossil fuel combustion produces all six criteria pollutants. Each criteria pollutant is described below individually. *Exhaust from motor vehicles accounts for about half of these emissions* (Table 5.1). When you examine Table 5.1, notice the words particulates and aerosols.[1]

Carbon monoxide

Carbon monoxide (CO) is pervasive. All by itself, CO accounts for more than 50% of air pollution nationwide and worldwide. Worldwide, hundreds of millions of tons are emitted yearly (Box 5.2). CO is a colorless, odorless, flammable gas; it is a product of incomplete

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[1] The gaseous pollutants, sulfur dioxide and nitrogen oxides, can be chemically transformed in the air to *aerosols*. Aerosols are a gaseous suspension of fine solid or liquid particles (*particulates*). A number of volatile organic pollutants also form aerosols. Metals are ordinarily directly emitted as particulates.

Table 5.1 Ambient air pollutants

Pollutant	Characteristics or examples
Criteria pollutants	**Six pollutants for which ambient air standards are set to protect human health and welfare**
Carbon monoxide (CO)	Produced by combustion of fossil fuel and biomass. All by itself, CO represents more than 50% of air pollution. Motor vehicles are the major source of CO, especially in cities.
Ozone (O_3)	A major component of photochemical smog formed from NO_x, VOCs, and oxygen in the presence of sunlight and heat. Motor vehicles are major generators of NO_x and VOCs.
Sulfur dioxide (SO_2)[a]	SO_2 is oxidized in air[b] to sulfuric acid under moist conditions, or to sulfate in dry conditions. Both are particulates and major components of haze. Fossil-fuel-burning power plants produce about two-thirds of the SO_2.
Nitrogen oxides (NO_x)[a]	NO_x are oxidized in air[b] to acid under moist conditions or to nitrate in dry conditions. Both are particulates and components of haze. In cities, motor vehicles generate most NO_x. Coal-burning facilities also produce significant quantities.
Lead (Pb)[c]	Lead is emitted as a particulate during metal mining and processing, and during fossil fuel combustion.
Particulates (PM_{10} and $PM_{2.5}$)	Tiny solid particles composed of one or several chemicals, and with many sources. Combustion is a major source of the tiniest particles. Notice that lead is emitted as a particulate and that SO_2 and NO_x can be converted to particulates; so can some organic VOCs.
Volatile organic pollutants (VOCs)[d]	**Organic chemicals that evaporate easily. Some significantly contribute to smog. Motor vehicles are a major source.**
Hazardous air pollutants (HAPs)	**Each HAP has an emission control, no ambient air standard is set. HAPs are also called toxic air pollutants. About 70% are also VOCs.**
Organic chemicals[d]	Examples are benzene, formaldehyde, and vinyl chloride.
Inorganic chemicals[c]	Examples are asbestos and metals such as cadmium and mercury.

[a] Some SO_2 and NO_x are converted to particulate forms (aerosols).[1]

[b] Air contains oxygen which reacts with, *oxidizes*, sulfur dioxide.

[c] Most emitted metals are already particulates.

[d] Some VOCs and some organic HAPs are converted to particulates (aerosols).

combustion of carbon-containing material. Only under ideal conditions, with an excess of oxygen and optimal burning conditions, is carbon completely oxidized to carbon dioxide (CO_2).

Box 5.2

Don't confuse carbon *mon*oxide with carbon *di*oxide. Carbon monoxide (CO) is an incomplete product of combustion, and toxic at small doses. Carbon dioxide (CO_2) is a complete product of combustion, and is much less toxic.

Why carbon monoxide is of concern

Even levels of CO found in city traffic can aggravate heart problems. CO causes up to 11% of hospital admissions for congestive heart failure in elderly people. Examining how CO works will clarify how it adversely affects the heart, and causes other adverse effects. The blood protein *hemoglobin* contains an iron atom, which normally picks up oxygen in the lungs and transports it to the body's cells. There hemoglobin releases oxygen, exchanging it for the waste gas, carbon dioxide (CO_2). It carries carbon dioxide back to the lungs, releases it, and once more picks up oxygen. CO is so toxic because it has 250 times greater affinity for the iron atom in hemoglobin than does oxygen – it displaces oxygen; so less oxygen reaches the heart. Even relatively small displacements affect heart function in sensitive people. The brain too demands a steady oxygen concentration for optimum functioning, so CO can cause headache, dizziness, fatigue, and drowsiness. At higher doses, such as found in enclosed spaces with improperly operating combustion appliances CO may lead to coma and death (Chapter 17). The US ambient air standard for CO is 9 ppm averaged over 8 hours; if this is exceeded more than once a year in a particular area, then the area is violating the standard.

Sources and sources of exposure

CO is formed anywhere that a carbon-containing material is burned, so CO exposure can happen anywhere that combustion occurs. ■ In urban areas, up to 80 or 90% of CO is emitted by motor vehicles. Drivers stalled in traffic, or driving in highly congested areas, can have high exposure; so can traffic control personnel, mechanics working inside garages and parking garage attendants. ■ Cigarette smoke contains CO too. Individuals with CO exposure at work, and who also smoke, increase their risk of adverse effects. ■ Facilities burning coal, natural gas, or biomass are CO sources. ■ Biomass combustion (wood, dried manure, other dried vegetation) can lead to significant CO exposure in rural areas, and in impoverished locales where biomass is burned for cooking, heating, and even light. ■ Atmospheric oxidation of methane gas and other hydrocarbons can produce CO too.

Reducing carbon monoxide emissions

In the 1950s, CO levels began to increase along with increasing combustion. The 1970s began a slow but steady downward trend as increasingly stringent emission controls were imposed in the United States and elsewhere. The following measures helped to achieve this reduction: ■ The EPA established national standards for tailpipe emissions. About half of motor vehicle CO emissions in the United States come from only 10% of the vehicles. Inspection programs attempt to find such vehicles, and see to their repair or removal from the road. Owners need to maintain their vehicles to allow them to operate as cleanly as the designers intended. ■ Facilities burning fossil fuels or wood are required to maintain high burning efficiencies to reduce emissions. ■ Many places prohibit open burning of trash and garbage.

Table 5.2 | Ozone levels

Concentration (ppm)	Air quality
0.00–0.05	**Good.** No health impacts expected
0.051–0.100	**Moderate.** Unusually sensitive people should consider limiting prolonged exertion outdoors.
0.101–0.150	**Unhealthy for sensitive groups.** Active children and adults, and those with asthma or another respiratory disease should avoid prolonged outdoor exertion.
0.151–0.200	**Unhealthy.** Active children and adults, and those with respiratory disease should follow the advice for 0.101–150 ppm. Others, especially children should limit prolonged outdoor exertion.
0.201–0.300 **Alert**	**Very unhealthy.** Active children and adults, and those with respiratory disease should avoid all outdoor exertion. Others, especially children, should limit outdoor exertion.

Healthy individuals exercising outside in 'unhealthy' periods should do so in early morning hours before ozone levels begin to climb (see www.epa.gov/airnow).

- Oxygen-containing fuel additives are added to gasoline in some US cities to enhance burning in winter, when engines run less efficiently. What happened in 20 cities illustrates how oxygenated fuels can make a difference. In the winter of 1991 to 1992, 20 cities exceeded the EPA's CO standard on 43 days. One year later, 1992 to 1993, after introducing oxygenated fuel, they exceeded the standard on only 2 days. Between 1988 and 1997, the number of times that the standard for CO (9 ppm) was exceeded, dropped 95%. The EPA called this "astonishing." Western Europe also tightened CO emission standards, and levels fell there too.

Ozone

Ozone (O_3) has three oxygen atoms. It is related to the molecular oxygen (O_2) necessary to our lives, which has two. Many of us know the odor of ozone from lightning storms or from improperly maintained equipment such as photocopiers. O_3 is a summer pollutant. It is found in photochemical smog (Box 5.3). Ground-level O_3 is the same O_3 that is found in the stratosphere. However, ground-level (tropospheric) O_3 is a pollutant whereas in the stratosphere, O_3 depletion is the problem (Box 5.3). Most ground-level O_3 comes from human activities. However, O_3 is formed naturally in areas remote from human activity, but at low levels, 0.02 to 0.05 ppm (Table 5.2).

Box 5.3 | Smog and ozone

The word, smog, as used today refers to *photochemical smog* because sunlight plays a major role in its formation. O_3 is a major component of photochemical smog, but smog contains other photochemical oxidants too, including peroxyacetyl nitrate (PAN) and nitrogen dioxide. And smog contains particulate matter making it "air you can see."

The first use of the term "smog" came from London in 1905. It describes the *sm*oke and f*og* combination that then commonly obscured visibility. This smog results from the sulfur dioxide, soot, and tarry materials that are produced from uncontrolled burning of high-sulfur coal. This still happens today in places without the technology to capture sulfur dioxide. In the first half of the twentieth century, severe episodes in England and the United States caused thousands of deaths.

Don't confuse ground-level (tropospheric) O_3 with stratospheric O_3. Ground-level O_3 is a serious pollutant, but in the stratosphere (the atmospheric layer above the troposphere), O_3 performs a vital function. It absorbs the sun's harmful ultraviolet rays, thereby protecting life on Earth.

Why care about ozone?

Oxygen (O_2) makes up about 20% of the air we breathe. Although essential to life, oxygen is reactive enough to sometimes harm us and other life. O_3 is much more reactive than O_2. The EPA considers O_3 the most serious and persistent air quality problem in the United States. It describes O_3 as the "most . . . intractable air pollutant in urban air." Moreover, O_3 is often present at levels known to have deleterious health and ecological effects.

- Effects on people. The acute health effects of O_3 are to irritate eyes, nose, throat, and lungs and to decrease the ability of the lungs to function optimally. At 0.2 ppm young adults develop inflammation of the bronchial tubes and tissue deep within the lungs. Even at 0.08 ppm, O_3 adversely affects some people, including healthy individuals. Exercising people are especially susceptible, and so are advised to exercise early in the morning on days when O_3 levels are unhealthy (Table 5.2). People with asthma or bronchitis, especially children, are also highly susceptible to O_3; it can also increase susceptibility to infection. Chronic O_3 exposure can permanently damage lungs.
- Effects on plants and trees. In the Los Angeles of the 1940s, it was observed that O_3 was greatly damaging vegetable crops. O_3 is primarily generated in the heavy traffic of urban areas, but its life span of weeks allows it time to spread over wide regions. The US Department of Agriculture reports that: "ground-level ozone causes more damage to plants than all other air pollutants combined". Estimated crop losses in the United States are 5% to 10%. O_3 damages sensitive crops at 0.05 ppm whereas more resistant crops withstand 0.07 ppm or higher. ■ Worldwide, perhaps 35% of crops grow in areas where O_3 levels exceed 0.05 to 0.07 ppm. If trends continue, by 2025 up to 75% of the world's crops will grow in areas with damaging O_3 levels. Trees are adversely affected too. Many foresters consider O_3 the air pollutant most damaging to forests. In areas with acid precipitation and other air pollutants too, the combination may be more damaging than the effects of any one pollutant alone.

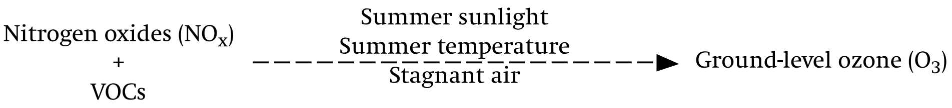

Figure 5.1 Formation of ground-level ozone

Sources of ozone

Remember that O_3 is not usually emitted as O_3; that is, it is not a primary pollutant. Rather O_3 is formed from *precursors*. Motor vehicles are a major source of the O_3 precursors, VOCs and NO_x. In the summer's heat and the sun's strong ultraviolet rays, VOCs and NO_x react with atmospheric oxygen (via several steps) to generate O_3 (Figure 5.1). Knowing how ozone is formed, you may surmise, correctly, that in a city O_3 builds up over the progress of a summer day: O_3 levels are typically low early in the morning. Then vehicle exhausts from the morning traffic increase atmospheric levels of NO_x and VOCs. As the day progresses, it becomes warmer, the sun's ultraviolet rays stronger, and O_3 is generated. Of course, off-road motor vehicles also contribute emissions; so do airplanes, construction equipment, lawnmowers and other garden equipment. ■ Yet other sources of O_3 precursors include facilities that burn fossil fuels and emit VOCs and NO_x, especially coal-burning electric power plants and industrial facilities.

Reducing ground-level ozone

As you see in Figure 5.1, we cannot reduce ground-level O_3 unless we reduce NO_x and VOCs emissions; that is, the chemical precursors of ozone. Billions of dollars have been spent to do this, often with unsatisfactory results. ■ Motor vehicles. *A major reason for our inability to lower O_3 is our inability to control motor vehicles*, which, in urban areas emit more than half of the NO_x and 40% of the VOCs. Motor vehicles were designed to run much more cleanly after passage of the 1970 US Clean Air Act, and emissions fell 90% or more per gallon of fuel burned. Unfortunately, at the same time the number of motor vehicles continued to rise, as did the number of miles driven per vehicle. So NO_x and VOC emissions remain high. In the early twenty-first century the United States has a new O_3 standard, which primarily affects – not industry – but communities with heavy traffic. Many communities are out of compliance with even the older, higher standard of 0.12 ppm. Poorly maintained vehicles, even if quite new, have much greater NO_x and VOC emissions than well-maintained ones. ■ Technical difficulties. One difficulty in reducing ground-level O_3 is that regulations designed to reduce VOCs or NO_x don't necessarily lead to the O_3 reductions anticipated. This happens because the reactions leading to O_3 formation are not as straightforward as Figure 5.1 seems to indicate. Still, efforts have paid off. Within the United States, the number of cities exceeding the old O_3 standard fell from 97 in 1990 to 56 in 1992. Nonetheless, in 1995 more than 70 million Americans still lived in areas not meeting the EPA's old 0.12 ppm O_3 standard. ■ Reducing other NO_x and VOC sources. Not only motor-vehicle emissions are being limited. There are controls too in industrialized countries on NO_x emissions from power plants and industrial facilities. There are also limitations on how factories can use solvents (with the purpose of limiting VOC emissions). Another measure is vapor-recovery nozzles on gasoline pumps that reduce VOC emissions during refueling; in addition, gasoline is being reformulated to burn more cleanly and thus to emit lower amounts of VOCs. Regular inspection of motor vehicles is also particularly important to make sure they are running cleanly. ■ Research. Researchers found that not all VOCs are equally important to O_3 formation. The VOC formaldehyde contributes much more than some other VOCs. This knowledge may lead to efforts to reduce specifically emissions of VOCs that contribute most heavily to O_3 formation. ■ Non-technical approaches. Technological changes to reduce emissions per vehicle or per factory are not enough. We must address social issues. How do we reduce our use of fossil fuels? How do we change the way we buy and use vehicles? More on our individual use of fuels, especially fossil fuels will come up in Chapter 13.

A changing ozone standard

This text has emphasized that a major difficulty in setting good health-based standards is that we lack good data. O_3 is an exception. There is abundant information on O_3 effects in animals and people, including volunteers exposed to O_3 in enclosed chambers. Thus, when the EPA re-evaluated its previous standard ("safe" dose) of 0.12 ppm, it found evidence that the standard was not protective enough. It was harming humans, crops and trees.[2] However, we can't really determine a safe dose for O_3 because it causes a biological response right down to background levels. Further complicating the issue is the fact that the difference between adverse effects on children playing outside at the old 0.12 ppm standard, as compared to the new (0.08 ppm), may be small. Thus, the US EPA was told by its Clean Air Scientific Advisory Committee that setting an O_3 standard was more of a policy call than a scientific judgment. In 1997, the EPA did set the new standard at 0.08 ppm. But only in 2002, after legal challenges ended, could the EPA move forward to implement the standard. Meanwhile, in 2003, one-third of Americans continue to live in areas that do not comply with the old 0.12 ppm standard. An instance is Los Angeles with 30 to 40 days a year above 0.20 ppm. There are O_3 successes nonetheless. Most US, Mexican, and Canadian cities manage, through emission controls, to at least keep O_3 levels

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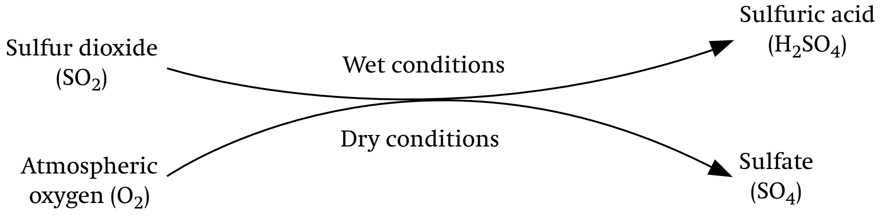
[2] Recall from Chapter 4 (for chemicals that are not carcinogens) the procedure for setting standards. A dose that does not harm laboratory animals is first determined (a no observed adverse effect level, NOAEL). Then a safety factor is applied to the NOAEL to determine a standard that is safe for human exposure.



Sulfuric acid and sulfate are aerosols. These wash out with rain, or slowly settle out by gravity. Both are acidic deposition.

Figure 5.2 Transforming sulfur dioxide to sulfuric acid and sulfate

fairly steady. And cities do this in the face of ever-increasing population and increasing motor-vehicle pressures.

Sulfur dioxide

Sulfur dioxide (SO_2) is a colorless gas with a sharp irritating odor. It accounts for about 18% of all air pollution, making it second only to CO as the most common urban air pollutant.

Why care about sulfur dioxide?

- Direct exposure to the gas, SO_2. The SO_2 gas reacts with moisture in the eyes, lungs, and other mucous membranes to form strongly irritating acid. This reaction removes about 90% of the SO_2 in the upper respiratory tract. Exposure can trigger allergic-type reactions and asthma in sensitive individuals (as do sulfites used in food preservation). Exposure also aggravates pre-existing respiratory or heart disease. And, as with O_3, low SO_2 concentrations can damage plants and trees.
- Aerosol effects. SO_2 itself has a lifetime in the atmosphere of only about a day. Thus, if the problems just noted were the only ones, SO_2 would be more manageable. However, SO_2 is converted into sulfuric acid if moisture is present, or, into sulfate particulates in dry conditions (Figure 5.2). These tiny particulates, only 0.1 to 1 μm in diameter, are *aerosols*. Aerosols are a gaseous suspension of fine solid or liquid particles. Exposure to sulfate aerosols can affect health because the tiny particles can be deeply inhaled into, and inflame, the lungs.
- Major environmental effects of aerosols. The aerosols also have major environmental impacts. ■ Aerosols form a haze that affects visibility. Haze also affects the level of sunlight reaching the Earth (Box 5.4). ■ The acid particulates formed are part of the acid deposition (acid rain) problem. ■ The particulates don't directly destroy stratospheric O_3, but do provide surfaces on which O_3-destroying reactions can occur. ■ Aerosols have a cooling influence on climate. These impacts are shared with nitrate and nitric acid aerosols (Table 5.3).

Box 5.4 Food production and sulfur dioxide emissions

China, a nation of 1.3 billion people burns coal to generate most of its electricity, and is the world's largest emitter of SO_2. A study sponsored by the US National Aeronautics and Space Administration, and the Georgia Institute of Technology found disturbing results: haze resulting from sulfuric acid and sulfate aerosols is cutting agricultural production. This happens because haze partially filters out the solar energy reaching the plants. Researchers estimated that the haze reduces sunlight by 5% to 30%. Moreover, decreased sunlight is affecting up to 70% of China's agricultural areas. This is particularly disturbing. With its huge and still-growing population, China already faces the prospect of needing to import food. If crop production is much hindered by pollution, the situation could be even worse. However, there *are* solutions. One is installing technology to lessen SO_2 emissions. Indeed, China is making major efforts to change how it uses energy. It has closed many small inefficient industrial facilities, started to burn cleaner coals (with less sulfur), and it has switched many residents, who previously burned coal, to gas or electricity.

Sources of sulfur dioxide

In the United States and the industrialized northern hemisphere, human activities produce *five times more SO_2 than do natural sources*. Worldwide, the figure is about two times as much. ■ In 1985, electric utilities burning fossil fuels produced about two-thirds of the anthropogenic (produced by human actions) SO_2 in the United States. The worst offenders are utilities that burn high-sulfur coal. ■ Metal smelters and other fossil-fuel-burning industrial facilities produce another 15% to 20%. Smelters emit SO_2 because many metal ores contain sulfur. ■ Petroleum contains sulfur too, but it can be more readily removed than that in coal, and motor vehicles account for a lesser percentage of SO_2 emissions. Also see Figure 6.1.

NATURAL SOURCES

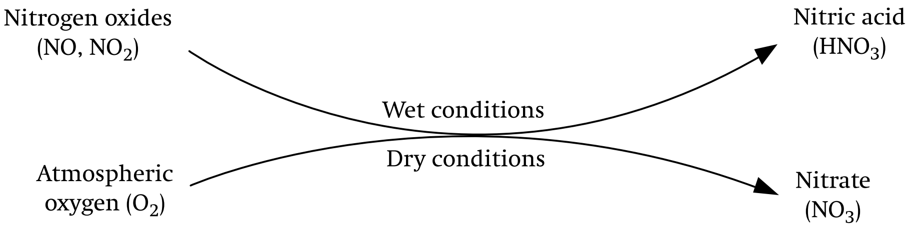
Although most SO_2 comes from human activities, there are many natural sources. These include sea water, marine plankton, bacteria, plants, and geothermal emissions. Erupting volcanoes are a major but periodic source of SO_2. In 1991, the Filipino volcano Mt. Pinatubo ejected about 20 million tons (18.1 million tonnes) of SO_2 into the atmosphere. This huge quantity is believed to have been responsible for cooling the Earth's climate for several years thereafter.

Reducing sulfur dioxide emissions

Over the past 30 years many nations have mandated emission controls on coal-burning electric power plants and other industrial sources of SO_2 – see the Chapter 6 section on reducing emissions of acid precursors.

Nitrogen oxides

The gases, nitric oxide (NO) and nitrogen dioxide (NO_2) are the major components of nitrogen oxides (NO_x, pronounced "knocks"). See



Nitric acid and nitrate are aerosols and wash out with rain, or slowly settle out by gravity. They are acid deposition in both cases. Importantly, they are also plant nutrients.

Figure 5.3 Transforming NO$_x$ gases to nitric acid and nitrate

Figure 5.3. A third gas, *nitrous oxide* (N$_2$O) is also often grouped into NO$_x$. Nitrogen oxides account for about 6% of US air pollution.

Why care about NO$_x$?

- Human health. Direct exposure to NO$_x$ gases irritates the lungs, aggravates asthma, and lowers resistance to infection. Nitrogen dioxide is poisonous to plant life. Converted to the aerosols, nitric acid and nitrate, there can be major deleterious effects. ■ The tiny aerosols can be deeply inhaled into, and cause inflamation of, the lungs.
- Major environmental effects. ■ Formation of haze that affects visibility. ■ Acid deposition (acid rain) ■ Stratospheric O$_3$ depletion because the aerosol particles provide surfaces on which O$_3$-destroying reactions can occur. ■ Cooling influence on climate. Notice that the above-mentioned effects are shared with sulfate and sulfuric acid aerosols (Table 5.3).
- Remember the following: NO$_x$ has two distinctive and very important effects not shared with sulfate and sulfuric acid. These are: ■ NO$_x$ gases are precursors of ground-level O$_3$ whereas SO$_2$ is not. ■ Deposited to Earth or water, the nitrogen in nitrate and nitric acid is a major plant nutrient. It can benefit plant life, *but* high concentrations have adverse, even devastating, consequences.

NO$_x$ sources

Nitrogen compounds are present in fossil fuels only in very small amounts – they are not a large source of NO$_x$ gases. ■ The reason that NO$_x$ forms is distinctive. Atmospheric nitrogen, N$_2$ is a very stable chemical. However, burning fuel at a high temperature promotes a reaction between N$_2$ and atmospheric oxygen, O$_2$. It is this reaction that results in NO$_x$ formation.

- Human sources. ■ NO$_x$ gases are emitted almost anywhere that combustion occurs, especially at high temperatures. This is unfortunate because high temperatures otherwise promote *efficient combustion* and lower the emissions of CO, PAHs and other incomplete

Table 5.3 | Sulfur dioxide, nitrogen oxides, and global change

Issue	**Role of sulfur dioxide (SO_2)**
Acid deposition	SO_2 emissions are converted in the atmosphere to sulfate and sulfuric acid – major contributors to acid deposition (Chapter 6).
Stratospheric-ozone depletion	Volcanic eruptions inject SO_2 into the stratosphere and it is converted to particles. Analogous to ice particles at the poles, these provide surfaces on which O_3-depleting reactions occur (Chapter 8).
Global climate change	SO_2 is converted to sulfate or sulfuric acid particles. These have "anti-greenhouse" effects. They do so by absorbing part of the sun's radiation, preventing it from reaching and warming the Earth's surface (Chapter 7).
Issue	**Role of nitrogen oxides (NO_x)**
Acid rain, stratospheric O_3 depletion, and climate change	NO_x emissions are converted in the atmosphere to nitrate and nitric acid, which contribute to the problems shown on the left.
Ground-level O_3	NO_x, but *not* SO_2, is converted to ground-level O_3 (Chapter 5).
Nutrient pollution	NO_x is converted to nitrate and nitric acid. After deposition to Earth and water, these can "over-fertilize" waters leading to eutrophication (Chapter 9).

products of combustion (Box 1.2). ■ As is true of CO, the major source of NO_x is motor vehicles, including off-road vehicles such as construction equipment. Motor vehicles account for more than 50% of NO_x emissions overall, and a greater percentage in urban areas. ■ Electric utilities in the United States emit another 25% to 30% of NO_x, and industrial combustion about 14%. Smaller amounts result from commercial and residential combustion.

- Natural sources. ■ NO_x gases are produced by lightning and volcanoes. ■ Microbes decomposing vegetation in soil produce nitrous oxide (N_2O). If nitrogen fertilizer is added to the soil they produce even larger amounts.

Reducing NO_x emissions

See Chapter 6 for means of reducing NO_x emissions.

Particulate matter

What is particulate matter?

Any gas such as N_2, O_2, or SO_2 blends into air in a homogeneous manner. *Particulate matter does not.* As the name particulate matter (PM) implies, PM is solid, albeit the particles may be very fine aerosols (again see footnote 1). PM accounts for about 10% of US air pollution. PM is a confusing pollutant.

- Composition varies. Other criteria pollutants are specific chemicals, CO, O_3, SO_2, NO_x, and lead. But, PM has no fixed composition. A particle may contain only one chemical such as sulfate, sulfuric acid, or lead. Another particle may contain a number of pollutants, e.g. sulfate, nitrate, metals, dust, biological matter, etc.

- Size varies greatly. PM may be as large as visible cotton dust, historically found in fabric mills. Or, PM can be tiny, submicroscopic particles, aerosols. Indeed, it is these tiny particles – even at low concentrations – that now pose major problems.
- Other pollutants can become PM. Table 5.1 shows particulates as a separate pollutant. However, a number of other pollutants can be converted to particulates. In Figures 5.2 and 5.3, you saw that gases, SO_2 and NO_x, are converted to the aerosols, sulfate and sulfuric acid, and nitrate and nitric acid. Such conversion to PM is not unique. Some organic vapors, VOCs, condense into particulates. Many hazardous air pollutants (see below) are metals, and thus are emitted as particulates. (Elemental mercury, largely emitted as a vapor is an exception.)

Why care about PM?

- Health effects. The idea of a particle seems innocuous – a tiny piece or speck – not something to inspire alarm. The reality is different. ■ Before the advent of workplace protection laws PM took a terrible toll. Workers with chronic exposure to silica dust developed silicosis. Coal miners, over their years of working, developed black-lung disease from coal dust. Textile workers developed brown-lung disease from cotton dust. Workers inhaling airborne asbestos developed asbestosis, lung cancer, or mesothelioma. All these diseases are disabling or deadly. Many workers inhaled large quantities of all sizes of particles, overwhelming their respiratory systems. ■ With less-extreme exposure, larger particles of dirt, dust, or pollen catch in the nose, throat, or windpipe, and can be sneezed, coughed, swallowed, or spat out. ■ At the beginning of the twenty-first century, it is the very tiniest of particulates that most trouble us. The US EPA regulates particles with diameters of 10 μm or less (PM_{10}), and an even more dangerous category with diameters of 2.5 μm or less ($PM_{2.5}$). The diameter of $PM_{2.5}$ is barely one-fortieth of the width of a human hair. Sulfate particles, and some soot and dust particles are as small as 0.01 μm. Deeply inhaled, they reach and can inflame the lung's alveoli (tiny air sacs where oxygen is exchanged with carbon dioxide). The very smallest may be absorbed into the bloodstream and exert systemic effects elsewhere in the body. The relationship between $PM_{2.5}$ and disease is remarkable (Box 5.5).
- Environmental effects. The health impacts of tiny particulates can be bad, but PM also strongly contributes to the haze or smog seen in many cities and often spreading far into rural areas. Sulfate and sulfuric acid aerosols in US parks illustrate this. Haze has reduced visibility in western national parks by up to 50% compared with earlier years. In eastern parks, which are exposed to a greater number of emission sources, haze has reduced visibility by 80% compared with the 1940s. Just in the 1980s, the Shenandoah and Great Smoky Mountains parks in Virginia and North Carolina saw a 40% increase

in sulfate particles. Instead of blue sky, one often sees pale-white haze or gray fog composed of dilute sulfuric acid. This increase in sulfuric acid and sulfate hazes in the 1980s happened as sulfur dioxide emissions nationwide were decreasing. There is much that we don't yet understand. ■ Beyond haze, individual particulates contribute to a variety of other problems depending on what they contain. The sulfate and sulfuric acid particulates, of course, are a major component of acid deposition.

Box 5.5 | A relationship with cancer and death rates

Epidemiological studies continue to indicate relationships between fine-particle pollution and death rates among sensitive individuals. Studies reported, for instance, that more deaths from heart and lung diseases occurred in a given locale on days with high levels of fine particles in the air, even levels in compliance with the pre-1997 particulate standard. The fine particles believed to be most responsible, $PM_{2.5}$, consist of sulfate or nitrate particles, soot, and other chemicals resulting from burning fossil fuels in coal-burning power plants, manufacturing facilities, and motor vehicles. You are probably not surprised that inhaled PM causes respiratory problems. However, reputable 1990s studies reported increases in heart disease and lung cancer after long-term exposure to $PM_{2.5}$.

The strongest work supporting a lung-cancer association was reported in 2002 in the *Journal of the American Medical Association*[3]: Canadian and American researchers tracked 500 000 people from 1982 to 1998. They reported the causes of all the deaths that occurred in these people over these years, and looked at levels of $PM_{2.5}$ in the air of the areas where those individuals had lived. They corrected results for confounding factors including occupational exposure, age, sex, race, smoking, drinking, obesity, type of diet (fat, vegetable, fruit, and fiber intake), and other risk factors, and used improved statistical techniques. Their finding? Every 10-μg increase in airborne fine particles ($PM_{2.5}$) per cubic meter resulted in a 6% increase in the risk of death from heart or lung disease, and an 8% increase for lung cancer. Risk was particularly increased in Los Angeles, but also in Chicago and New York City, and in rural areas with coal-burning power plants. The risk was higher among the elderly, and those already suffering from heart disease, or lung diseases such as asthma and bronchitis. One study leader commented, "This study provides the most definitive epidemiological evidence to date that long-term exposure to air pollution in the United States is associated with lung cancer."

But how could PM cause disease? For a long time particulate studies were criticized because many particles contain more than one chemical – to which chemical(s) do we attribute the diseases seen? The same criticism was made earlier of relationships between second-hand tobacco smoke (among people living with a smoker) and lung cancer. However, in both cases the particles contain a number of carcinogens such as PAHs (see Box 5.7). In both cases, tiny particles are trapped and retained in the lungs. However, we do need more research. Which PM chemicals are most responsible for the effects observed? How do they promote lung cancer and heart disease?

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[3] *Journal of the American Medical Association*, 2002.

Sources of PM_{10} and $PM_{2.5}$

- PM_{10}. The major source of PM_{10} is dust from farms, mines, or from roads, unpaved and paved. PM_{10} also includes pollen. Only about 6% of PM_{10} comes from burning fossil fuels.
- $PM_{2.5}$. Conversely, most $PM_{2.5}$ *does* originate from combustion, especially diesel motor vehicles, electric power plants, and industrial operations such as steel mills emitting SO_2. In the United States electric power plants emit about two-thirds of the SO_2, which becomes sulfuric acid and sulfate aerosols that contribute to haze. ■ Power plants and other incinerators also produce *fly ash*, whose very fine particles contain many metal oxides and silicon dioxide. Silicon dioxide is found in a benign form in window glass. But silicon dioxide in fly ash or fine blowing sand is not benign. Fly ash particles also hold on to dioxins formed during combustion. ■ When combustion is efficient, almost all organic material is converted to carbon dioxide and water, and little particulate matter and soot is formed. When combustion is less efficient, more particles form.
- Other PM sources. Although fossil-fuel combustion sources dominate PM emissions, especially $PM_{2.5}$, there are many other PM sources. Locales with large numbers of wood-burning stoves, which often burn inefficiently, contribute to particle levels. Rural areas generate airborne particles when burning biomass and from windswept dirt, fertilizer, dried manure, or dried crop residues. Particulates in coastal areas contain high levels of chloride (sea salts), which can corrode local buildings and monuments. Construction sites release large amounts of dust.

Reducing PM emissions

In 1997, the US EPA set new standards for particulates at the same time as its new standard for O_3. And, as is true with O_3, only in 2002 has the new PM standard withstood court appeals to allow its implementation. The old PM_{10} standard was 50 $\mu g/m^3$ of air; this standard is retained. However, to this was added a new PM standard specific to $PM_{2.5}$ of 15 $\mu g/m^3$.

But $PM_{2.5}$ poses quandaries as we contemplate how to reduce it.

- Despite excellent epidemiological information on the dangers of $PM_{2.5}$, major questions need answers before we can act most effectively to reduce $PM_{2.5}$ emissions: Example: $PM_{2.5}$ contains chemicals that are different on the US east coast compared with the west coast. Moreover, although almost everyone believes that $PM_{2.5}$ is responsible for adverse health effects, we don't know *what* component(s) within $PM_{2.5}$ is most responsible: sulfate, nitrate, elemental carbon, carbon compounds, or metal oxides. If we determine what PM chemicals are most dangerous, we could design more specific controls. This could reduce risk more efficiently and more cost-effectively than attempting to control all fine-particulate sources.
- Combustion. By now it is probably clear that controlling combustion sources producing PM is a major need. And remember that, as

was the case for CO, O_3, SO_2, and NO_x, we need to control combustion *sources*! For Americans, this would mean committing to lessened dependence on fossil fuels; still an unpopular proposal. The EU countries are focusing attention on means to reduce O_3 and PM too. When the European Union adopted its Clean Air for Europe (CAFE) program, these two were targeted as, "the air pollutants of greatest concern" in 2001.

Lead

Lead is described in Chapter 15 (Section II). In the 1970s, when the EPA designated it a criteria air pollutant, lead was still added to gasoline in the United States, incinerators were less well controlled than today, and lead emissions in general were less well controlled. Today, most lead emissions have been eliminated or are well controlled. Lead emissions from coal-burning power plants are an exception. ■ However, a separate set of lead-related problems exist. Lead mobilized into the environment many years ago, remains a significant pollutant today. It is in the paint of houses built before the late 1970s, in the solder of old water pipes, and in roadside soil contaminated with lead from car exhaust. Leaded gasoline is still used in a number of less-developed countries; so is leaded tableware. Recycling of lead-acid batteries in impoverished countries remains an occupational exposure even for children.

Questions 5.1

1. Under what circumstances might you be exposed to: (a) CO (b) O_3 (c) PM (d) SO_2 (e) NO_x?
2. How is the way you are likely to be exposed to sulfuric acid and sulfate different from your exposure to sulfur dioxide?
3. Environmental improvements can involve cost. Assume you want to convince your employer to conserve fossil fuels as a means of lowering criteria pollutant emissions. (a) Outline your arguments including non-environmental ones. (b) Which changes could be done at no cost? (c) Which changes involve up-front costs?
4. Your highest exposure to particulate matter, including fine particles occurs inside your home. Does this mean we can lessen our emphasis on regulating particulates in outside air? Explain.

Box 5.6 | A criteria pollutants update

If we add together the emissions of all six criteria air pollutants, the EPA tells us that, between 1970 and 2000, US emissions fell by about 29%. This occurred despite the fact that over those 30 years, energy consumption (a major cause of air pollution) increased by 45%, and the number of miles Americans traveled in motor vehicles (another major source of air pollution) increased by 143%. The picture is different if we examine emissions of individual criteria pollutants.

- Emissions of CO, SO_2, PM, and lead did drop significantly between 1970 and 2000; so did the volatile organic chemicals (VOCs), which are precursors of ground-level O_3.
- However, *nitrogen oxide emissions grew* 20% over that 30-year period, with half of the increase in the 1990s. And, because NO_x leads to ground-level O_3, O_3 also increased in certain regions. The EPA attributed the increased O_3 levels largely to NO_x emissions from fossil-fuel-fired power plants and motor vehicles.

Regulators usually consider pollutants one by one. An exception was the EPA's 1997 issuance of simultaneous new standards for ground-level O_3 and PM. The US Congress has also recently looked at strategies to further reduce emissions simultaneously of SO_2, NO_x, mercury, and even CO_2. Mercury emissions are the hardest to control because mercury is such a tiny proportion of the total stream coming from a coal-burning power plant. European countries are even more serious about developing a strategy to control pollutants as a group, SO_2, ammonia, PM, and the O_3 precursors, NO_x and VOCs.

Questions 5.2

1. What criteria air pollutant(s) would be of immediate concern to you in the following instances? Explain your answers. (a) You are a garage attendant or a traffic officer in a large city. (b) Air pollution from a nearby urban center reaches your farm. (c) A truck is parked near an air intake of the motel where you are spending the night. Because the truck contains perishables, its motor was left idling. (d) You are a park ranger in the Great Smoky Mountain National Park.
2. What have you learned about ozone and particulates that made it reasonable for them to be considered together when new standards were set?
3. Consider: "The more the population grows, the more the rights of the common will impinge on the rights of the individual." How is this statement relevant to regulating motor-vehicle emissions?

Volatile organic chemicals

A great many organic chemicals are volatile; that is, they can evaporate. These fall into the category of "volatile organic chemicals" (VOCs).[4]

Why care about VOCs?

VOCs contribute to the formation of ground-level ozone. And VOCs all by themselves can have adverse effects: many drivers and pedestrians develop headaches and other symptoms if heavily exposed to volatile hydrocarbons in motor vehicle exhausts. Sensitive individuals may

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[4] VOCs in city air often just refer to the volatile hydrocarbons (chemicals containing only carbon and hydrogen), which are emitted in large quantities in motor-vehicle exhausts. However, many VOCs contain other elements too: oxygen, nitrogen, sulfur, and others.

react with attacks of asthma or other respiratory problems. But ozone and other air pollutants also contribute to people feeling ill around heavy traffic.

VOC sources

- Combustion sources. Recall that hydrocarbons are the most common VOCs. Motor vehicles are the largest source of VOCs; they emit up to half of all VOCs in the United States. Look again at Box 1.2: inefficient internal combustion engines burn hydrocarbons inefficiently, and large amounts are emitted as incomplete products of combustion. Hydrocarbons also evaporate as gas tanks are filled, and when vehicles are running, idling, or cooling. Combustion engines are pervasive, used not only in cars, trucks, and buses, but also in airplanes, construction, farm and forestry equipment, gasoline-powered lawn and garden equipment.
- Non-combustion sources. Petroleum refineries, chemical plants and electric power plants can be important *local* sources, but compared with the VOC emissions of motor vehicles, these are small sources. Other non-combustion sources include a great variety of facilities including gasoline stations, vehicle maintenance shops, paint and print shops, dry-cleaners, wood-drying or wood-painting operations, even freshly painted houses. ■ Restaurants and bakeries emit pleasant-smelling VOCs, but large bakeries emit large amounts of ethanol formed by the action of yeast. ■ Sewage-treatment plants and composting operations emit VOCs too, often with objectionable odors.
- Natural sources. Trees and plants are a large natural source of hydrocarbons, especially in hot weather. Trees may be a significant source, even in large cities. In Maine, a heavily forested state, trees produce more than 90% of the state's VOCs. Among the many volatile compounds emitted by trees are the terpenes, responsible for the smell of pine trees. Pleasant smelling though they are, they can contribute to ozone formation. However . . . trees do *not* emit the NO_x that interacts with VOCs to form ozone. Although natural VOCs are not themselves a problem, they must be included in any strategy to reduce ozone formation.
- Homes and offices. Although we don't produce large amounts of VOCs in homes or offices, they can be a large source of human exposure. Paints, solvents, charcoal broiler starters, aerosol sprays, even deodorants and cosmetics all expose us to VOCs (Chapter 17).

Reducing VOC emissions

By 1985, VOC emissions had dropped about 30% compared with 1970 in the United States. This was presumably due to regulations enacted in the 1970 Clean Air Act (CAA) and its 1977 amendments. In 1990, CAA amendments mandated further reductions in motor-vehicle emissions. Regions of the United States with the worst air pollution had to commit to a 15% reduction in urban smog by 1996. Southern California has been especially aggressive in reducing not just VOC emissions from motor vehicles, but all vehicle pollutants. This state took measures that included switching to less-polluting fuels, and mandating that motor-vehicle manufacturers sell specified numbers of low-polluting or zero-polluting vehicles. ■ Other locales have taken actions such as highway lanes that can be used only by vehicles carrying more than one passenger, or tolls paid only by those who drive in peak-traffic hours. Sometimes employers pay employees to take alternative forms of transportation to work. Chapter 13 has more information on reducing motor-vehicle emissions.

Questions 5.3

The EPA reports that nearly 200 million tons (181 million tonnes) of five criteria air pollutants (sulfur dioxide, nitrogen dioxide, carbon monoxide, lead, and particulate matter) plus VOCs were emitted in the United States in 1997.

1. Ozone is a criteria pollutant – why wasn't this serious pollutant on this list?
2. Which of these five pollutants can be deposited into water and land?
3. What chemical changes must sulfur dioxide and nitrogen oxides undergo before they can be deposited into water and soil?
4. What happens to the large amounts of carbon monoxide that we emit to the environment?
5. What is the eventual fate of most VOCs in the environment? *Hint*. See Chapter 1.

SECTION II

Hazardous air pollutants

As is true of the term criteria air pollutants, legislation was the source of the term "hazardous air pollutants" (HAPs). Commonly called "toxic air pollutants," HAPs include 188 chemicals specified as hazardous in the 1990 US Clean Air Act Amendments; see examples in Table 5.4. *Many* additional chemicals could qualify as HAPs, but these 188 had a high priority.[5] HAPs are not unique to the United States. They are pollutants that might occur almost anywhere in the world. About 70% of HAPs are also VOCs; that is, volatile organic chemicals, whereas many others are metals. ■ *Do not conclude* that hazardous air pollutants pose greater problems than do criteria air pollutants. Criteria pollutants are hazardous too, and they are produced in much larger quantities typically than are HAPs.

Sources of HAPs and their adverse effects

The specific adverse effects of a particular HAP depend upon its intrinsic toxicity, and the amount to which a human, animal, or plant is

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[5] You may remember the Toxic Release Inventory, TRI from Chapter 2. Many of the 188 HAPs are also TRI chemicals. The emissions of such HAPs must be reported yearly.

exposed. It is not feasible to consider all HAPs individually, so only examples are given here. *Benzene* is a high-production chemical with many uses. One use is as an anti-knock agent in gasoline. Benzene can irritate the skin and eyes, cause headaches and dizziness. At the high levels once found in some workplaces, it was associated with leukemia and aplastic anemia. Benzene is found anywhere that gasoline is used: around motor vehicles, lawnmowers, and other equipment. Benzene is also present in cigarette smoke. Of all the HAPs, benzene is one of the most common. Exposure to benzene can be nearly ubiquitous. *Formaldehyde* is another high-production HAP. It is released from factories that manufacture furniture or pressed wood products. Formaldehyde can irritate the eyes and lungs. At high doses it is an animal carcinogen. Some people develop severe allergies to formaldehyde. *Chloroform* was used as an anesthetic for 100 years before its ability to cause liver damage was fully appreciated. It can also be toxic to the kidney and, at high concentrations, is an animal carcinogen. Chloroform is released from sewage-treatment plants, from pulp-bleaching facilities, and other facilities that use chlorine-containing chemicals. *Cadmium* is highly toxic and bioaccumulates in plants, shellfish, and animal kidneys and liver. It is a metal HAP emitted by metal-refining facilities and by manufacturing facilities that make cadmium-containing products. Incinerators emit cadmium in small amounts; so do facilities that burn fossil fuels. *Mercury* is a neurotoxin. It is a metal HAP, and the only metal that is liquid. Mercury is especially toxic after bacteria convert it to methylmercury, which biomagnifies in the food web; see also Table 5.4.

Other HAP concerns

An individual HAP poses the most concern at or near its point of emission. However, wind currents can carry the HAPs far from their sources. ■ Chloroform emissions are important only near the facilities that use chlorine-containing chemicals, such as municipal wastewater-treatment or pulp-bleaching facilities. ■ Several HAPs – benzene is a major case – are more widespread. Each benzene source may be local, but sources are ubiquitous. ■ Metal HAPs pose special problems because they are persistent. Metals have built up in soil and sediment in certain locations. And, because every motor vehicle that burns gasoline emits HAPs, there are many millions of small metal-emitting sources. On a larger scale, every fossil-fuel-burning power plant, and many industrial facilities, emit metals. ■ The greatest source of human exposure to HAPs such as benzene, formaldehyde, and a number of others, is often in our own homes (Chapter 17).

Reducing HAP emissions

Recall that each criteria air pollutant has an ambient air standard set for it, a standard that is based on its risk. However, setting standards is both time and money consuming, and by 1990 standards had not been set for many of the HAPs considered to be of high risk. As an

Table 5.4 | Examples of federally regulated hazardous air pollutants in the United States[a]

Pollutant	Representative sources or uses
Organic	
1. Benzene	1. Gasoline, cigarette smoke
2. Toluene	2. Gasoline, vehicle exhaust, smoking, paints
3. Ethylene glycol	3. Automobile antifreeze, brake fluid
4. Methanol	4. Windshield antifreeze, solvent
5. Chloroform	5. Formed during water chlorination
6. Methyl bromide	6. Fumigant
7. Formaldehyde	7. Particle-board and plywood, insulation, cosmetics
8. Parathion	8. Insecticide
9. Styrene	9. Manufacturing plastics, rubbers, adhesives, and cushions
10. Vinyl chloride	10. Manufacture of plastics, new automobile interiors
11. PAHs	11. See Box 5.7
Inorganic	
Asbestos (fibrous mineral)	Once widely used to fireproof materials
Metals	
1. Arsenic (metalloid)	1. Mining and smelting operations, glass making, petroleum refining, metal alloys
2. Cadmium	2. Electroplating, NiCad batteries, pigment and plastic stabilizer
3. Chromium	3. Electroplating (vehicle parts, bathroom fixtures), chemical catalyst
4. Mercury	4. Mercury measuring devices such as thermometers, also lamps, dental amalgams
5. Nickel	5. Electroplating, in alloys, chemical catalyst

[a] For a complete list see http://www.epa.gov/ttn/atw/188polls.html the US EPA's original list of hazardous air pollutants.

alternative to ambient air standards, the US 1990 Clean Air Act Amendments mandated "maximum available control technology" (MACT) to reduce HAP emissions from individual facilities. In the future, as more information on actual risk becomes available, emissions of some HAPs may be further restricted. There are other ways to reduce HAP emissions other than by regulation. ■ Before 1990, more than 1000 companies engaged in a voluntary program to reduce emissions of 17 HAPs produced in large quantities or that posed special risks. ■ HAPs are among the chemical emissions that must be reported on the Toxic Release Inventory. Such public declarations have led many facilities to work harder to reduce their emissions levels.

Box 5.7 | The ubiquitous PAHs

Like carbon monoxide, PAHs are products of incomplete combustion (Box 1.2). However, chemically, a polycyclic aromatic hydrocarbon (PAH) differs greatly from carbon monoxide, which is a simple albeit very toxic molecule. PAHs are polycyclic ("many ringed") hydrocarbons. They cling to sediments and soil, are difficult to degrade, can bioaccumulate in fat, and are toxic; that is, they are persistent, bioaccumulative, and toxic (PBT, Chapter 14).

- Toxicity. When breathed into the lung as fine particulates, PAHs can cause respiratory distress. Several PAHs are known human carcinogens; among these, benzopyrene is the strongest carcinogen. Recall (Chapter 4) that an excess risk of no greater than one in a million (or 1 in 100 000) is a goal for exposure to carcinogens. However, even rural soils (away from major highways) sometimes pose an excess risk close to one in a million, and PAH levels in urban soils pose a 100 to 1000 times greater risk still. Fortunately, PAHs are often not bioavailable; that is, they can be detected in soil, but bind so firmly that even if the soil is ingested, absorption is limited.
- Sources. More than 4 million tons (3.6 million tonnes) of PAHs are emitted into US air each year. They are a byproduct of combustion found anywhere that carbon-containing material is burned: wood, fossil fuel, plastic, cotton, a browned oven roast, or charcoal-grilled food. Natural sources include forest and grass fires and volcanic eruptions, and the natural components of petroleum. But it is coal burning and motor-vehicle exhausts that greatly increase environmental levels. Burning of agricultural wastes and wood burning are also significant in some locales.
- Exposure. Airborne PAH particulates settle into water. There, concentrated in sediment, PAHs are protected from the sunlight and warmth that could help destroy them. Airborne PAHs also settle onto soil, food crops, and other vegetation. In homes with cigarette smokers, tobacco is a primary route of PAH exposure. Otherwise, foods are the route of 90% of human exposure, especially leafy vegetables and unrefined grains. We also ingest PAHs when eating charcoal-grilled foods and browned, especially very brown, meats, baked goods, and toast. Smoking one or more packets of cigarettes a day can double, in some cases quintuple, a person's PAH exposure.
- Reductions. PAHs are particulates, so proper controls can capture a large portion of their emissions from, for example, fossil-fuel-burning facilities. Pollution prevention (P^2), reducing the amount of PAHs formed, is superior to controlling emissions of PAHs once they are formed. P^2 is promoted by using conditions that promote efficient burning. Becoming less dependent on fossil fuels is another P^2 approach. See http://atsdr1.atsdr.cdc.gov/tfacts69.html.

Questions 5.4

Before answering these questions, make sure you remember the difference between criteria air pollutants and hazardous air pollutants.

1. What actions can you take within your household to lower your PAH exposure?
2. (a) What if the 188 hazardous (toxic) air pollutants were called the risky air pollutants – how would the meaning change? (b) Consider the chemicals reported on the Toxic Release Inventory – what if it was called the Risky Release Inventory?

3. (a) What are several hazardous (toxic) air pollutants that may be emitted in your community? (b) Examine Table 5.4. To your knowledge, are any of these pollutants released in your community? If so which, and what is the source of the emissions? (c) To your knowledge, are you exposed to any of these, and how? (d) See the EPA's complete list of HAPs at: http://www.epa.gov/ttn/atw/188polls.html. Do you recognize any of these (in addition to those in Table 5.4)? If so, do you know their sources?
4. Burning gasoline in 200 million motor vehicles is the single largest source of ambient air pollution in the United States. Motor vehicles consume over half of petroleum used in the United States, and consume large quantities in other countries. It is also a national security issue. (a) Does this knowledge increase the likelihood that you might think carefully about fuel economy when you buy a motor vehicle, drive, and maintain it? Why? (b) If knowledge alone is not enough, what might change your behavior? (c) Under what circumstances do you now walk, take public transportation, or ride a bike? (d) Under what circumstances would you be willing to use these options more often?
5. (a) Social critics observe that the US regulates pollutant emissions and encourages P^2, but remains blind to the root causes of environmental damage, i.e., growing population and growing consumption. Do you agree? Explain. (b) Do you believe that we could lower our consumption while still maintaining what you personally would consider good living standards? Explain.
6. VOCs plus four criteria pollutants (carbon monoxide, sulfur dioxide, nitrogen oxides, particulates) account for about 98% of all air pollution. Fossil-fuel combustion is a major source of all five. (a) Assume that you believe that society should do more than it does now to reduce fossil-fuel dependence. What are three steps that should be taken? (b) What are three steps that you as an individual would be willing to take to reduce dependence on fossil fuels?

Europe

Details differ, but the European Union and other European countries have the same air pollutants and pollution problems as does the United States. These include: the effects on human health of smog and particulates, ozone damage to vegetation almost everywhere in Europe, and continuing acid deposition causing damage to soils, trees, and waters. ■ In late 1999 many European countries adopted a cooperative protocol to address these pollutants aggressively under the UN Convention on Long-Range Transboundary Air Pollution. This protocol was described as the "most sophisticated environmental agreement ever negotiated." Each country signing on was assigned ceilings on its emissions of sulfur dioxide, nitrogen oxides, volatile organic pollutants, and ammonia. The ceiling for each pollutant was individualized to the circumstances of each country. Countries are expected to reach the reductions assigned to them by 2010. By that year the 15 countries of the European Union as a whole expect

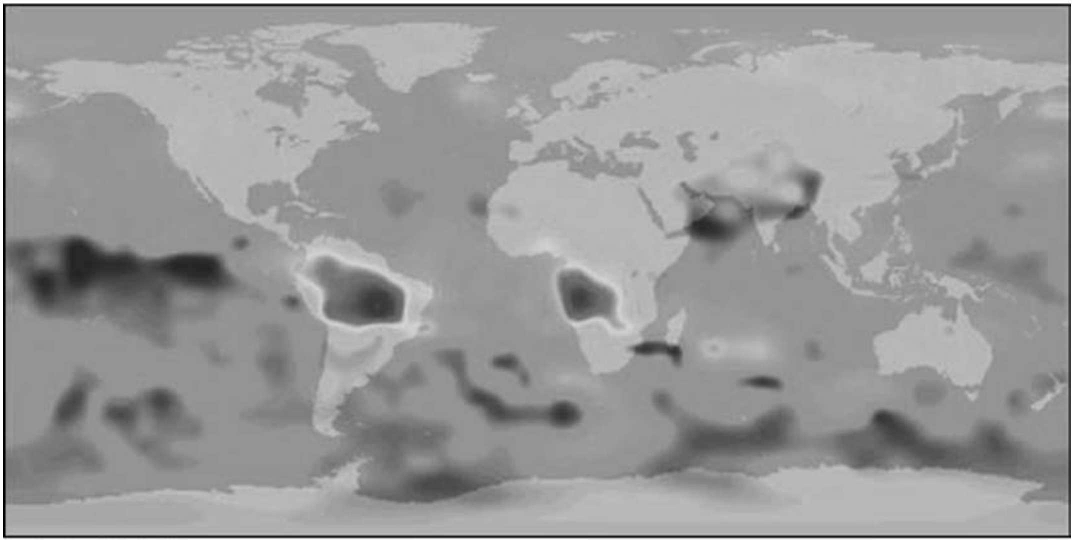

Figure 5.4 Carbon monoxide observed instrumentally from space. Carbon monoxide is the especially dark clouds traveling over the South American and African continents (30 October, 2000). Source: NASA Visible Earth web site (http://visibleearth.nasa.gov/Sensors/Terra/MOPITT)

a 63% cut in sulfur dioxide emissions, and a 40% cut for nitrogen oxides, VOCs, and ammonia.

SECTION III

Pollution from space

Carbon monoxide and smoke

To detect a pollutant such as carbon monoxide from space requires instrumentation. But some pollution, such as devastating fires or dust storms, can be directly observed from space.

Instrumental observation

"A spacecraft has captured the most complete picture yet of global air pollution." The NASA spacecraft, Terra began taking pictures of carbon monoxide from space in 1999 using MOPITT (measurements of pollution in the troposphere) instrumentation. MOPITT can visualize clouds of carbon monoxide traveling across the Earth's surface (Figure 5.4). It observes carbon monoxide 2 miles above the Earth's surface. From there, carbon monoxide rises to higher altitudes and continues traveling with wind currents. Under different meteorological conditions carbon monoxide sinks to the Earth's surface adding to ground-level pollution. Carbon monoxide is the only combustion pollutant that MOPITT can detect, *but* carbon monoxide serves as a tracer for nitrogen oxides and other combustion pollutants produced at the same time. MOPITT can observe emissions from a city, but cannot precisely pinpoint the source. MOPITT more clearly observes the enormous carbon monoxide clouds produced by forest and grassland fires in Africa and South America. These clouds travel across the southern hemisphere, as far as Australia, during the dry season. MOPITT also picks up other carbon monoxide sources and follows their travel patterns around the Earth. Because MOPITT can follow the pathways of pollutants and determine their concentrations, it is useful for mapping pollution around the globe and is expected to be helpful in setting international environmental policy.

Direct observation

Some fires and smoke clouds can be directly observed from an orbiting satellite. One set of mammoth fires that were observed occurred in 1997 in Indonesia's rain forests. These fires were described as a planetary disaster, "one of the most broad-ranging environmental disasters of the century." The fires were started deliberately as a means of clearing rain forests so that plantations of rubber, palm oil, rice, and timber could be planted. For weeks, a smoky haze fell over not just Indonesia, but Malaysia, Singapore, Thailand, Brunei, and Australia. Smoke aggravated or caused lung and other health problems. Factories and schools closed. Shipping was disrupted and airports closed. Crop yields fell as a perpetual twilight haze settled over the region. The damage was calculated at $6 billion, quite aside from long-term environmental and health damage, and the displacement of the forests' indigenous peoples and animals. Despite the world's appalled reaction to these fires, they happened again in 1999. Mammoth fires are not unique to Indonesia; they have occurred elsewhere too, especially in the Amazon rain forests.

Investigating the larger picture

The ability to observe carbon monoxide, smoke and dust from space is impressive. However, it has taken much effort to trace the origins, routes of travel, and environmental impacts of these and other traveling pollutant clouds.

- One question: What is the origin of pollutants, especially nitrogen oxides, that lead to smog in the New England States? Much nitrogen oxide was traced back to the US mid-west.
- Another question: Can the precursors of acid deposition arising in the eastern United States cross the Atlantic Ocean to reach Western Europe? The answer is yes. Whether the amounts transported are enough to significantly increase acid deposition in Europe is not yet known.
- What is the origin of the wintertime haze seen in the Arctic? This massive haze of metals and other particulates covers an area equivalent to 9% of the Earth's surface. It was traced to industrial emissions in Europe and Asia.

Struggling to understand the journeys of windborne pollutants, researchers ask increasingly complex questions. International teams work from aircraft, ships, ground-based stations, and satellites. Using increasingly sophisticated instruments, scientists follow pollution over Asia, Africa, Europe, North and South America, Australia, and Antarctica. The data gathered allows them to slowly piece together logical pictures of pollutant movement with the wind. The final destination of a traveling pollutant varies with seasonal storm conditions, and with the winds prevailing at different times of the year.

Mammoth quantities of particulate matter

Giant dust storms

Amounts of wind-transported pollutants range from very small to momentous. ■ One that is momentous is the great yellow clouds – these are observable from space too – created by giant dust storms (sand storms) in Mongolia's and China's growing Gobi Desert. Tracing this dust over thousands of miles, we see it carried across the Pacific Ocean to the United States. There, after crossing San Francisco on the western US coast, it moves east to Colorado. After one large Gobi storm in 2001, the dust reaching Boulder, Colorado reduced sunlight over the city by about 25% before moving onward in a path to the east. This dramatic effect occurred although the dust had, by the time it reached Boulder been traveling for over a week over the Pacific, spreading out and being diluted as it went. See Box 5.8.

TRAVELING DUST AND DISEASE

Think about another pollutant, dust originating in the African desert. This is blown across the Atlantic to the Caribbean Islands and to Florida. On some Miami summer days, the dust contributes upwards of *100* micrograms of particulates per cubic meter. Now, consider that the US EPA standard for fine particles (PM_{10}) is *15* $\mu g/m^3$ over a 24-hour period (or a 150 maximum for any single hour). Policy makers are taking notice of this pollution from afar, and gleaning data from scientists that may be useful in the future when setting air standards. ■ Strikingly, these traveling dust storms carry bacteria and fungi, some infectious. It is possible in the Caribbean to culture pathogenic bacteria, viruses, and fungi blown in from Africa. Much higher numbers of infectious agents were found on days when large quantities of dust blew in from Africa than on days bringing little dust. Coral researchers were able to link a fungus blown in from Africa to a major disease of the Caribbean Sea Fan. And fungal spores, transported from Cameroon in West Africa into the Caribbean's Dominican Republic, "almost certainly" caused rust disease in sugarcane, devastating that industry for a time. Two researchers, Brown and Hovmøller note, ". . . plant quarantine has restricted the movement of many pathogens, but it has not halted those that cause such destructive diseases." That, of course, is true because we cannot halt the windborne dispersal of these pathogens. ■ If these dust storms worsen, they may also carry significant amounts of chemical pollutants especially metals.

Why are dust storms increasing?

The answer includes both natural events and human activities. Intercontinental transport of dust storms has existed since time immemorial, but has worsened as human actions have aggravated the growth of deserts from which so much dust blows.

DRIED-UP WATER BODIES

Northern Africa's Lake Chad was once as large as Lake Erie in North America, but 50 years of drought combined with over-pumping of Chad's water for irrigation has resulted in a lake only 5% as large as in 1960. Moreover, Chad's now dry bed is "pumping dust everywhere, all year long, almost every day," to, depending on the season, Europe, the United States, and elsewhere. ■ The Aral Sea bordering Kazakhstan and Karakalpakstan was the world's fourth largest water body until the Soviets diverted its waters for farm irrigation. Now a huge portion of the lakebed is exposed to the wind. ■ In the State of California, 100 years ago, Owens Lake was the size of the Sea of Galilee. Then, its waters were diverted for use in Los Angeles. Owens Lake dried up exposing many thousands of hectares of salty silt, now it is "the biggest single dust source in the United States," and is greatly polluting nearby cities.

DESERTIFICATION

Another major cause of dust and sand storms is growing deserts (desertification) – these have become a major and urgent world issue. Desertification already affects nearly 1 billion people, and over 41% of the Earth's land area. The number of affected people may double, leading not just to more dust storms, but to increasing poverty and food insecurity. Desertification can be natural, as when it results from a long-lasting drought. However, increasing human populations place ever-increasing pressure on the world's dry lands. This leads to land misuse, including poor irrigation practices, livestock overgrazing, over-cultivation of soils, and deforestation. A natural drought can aggravate this situation. Desertification is most pronounced in Africa where 65% of the agricultural land may be degraded. It is an increasing problem in Latin America and Asia. In Mexico, 85% of the land is threatened by desertification, a situation that is believed to contribute to the immigration of nearly 1 million Mexicans a year to the United States as people move off land that is becoming unusable.

Reducing desertification

The Director of the UN Environmental Program, Klaus Töpfer says the world's response to desertification "must be equal to that demanded by global warming, the destruction of the stratospheric-ozone layer, and the loss of biodiversity." Desertification is not an insoluble problem, but it does require major effort and money to set up and maintain anti-desertification programs. Such efforts integrate the best of traditional agricultural practices including terracing and water harvesting. They also include very modern techniques, such as satellite imagery, to follow how well programs are working. Genetic engineering of animals and crops so that they are better able to live in these arid areas may also play an important role. When desertification has been caused naturally by a long drought, it may be reversed by normal rainfall over a period of time.

Box 5.8 | Pollution up close

Disastrous fires and mammoth dust storms may appear from space as "gigantic yellow blobs." However, living in the midst of a dust storm is different to observing it peacefully from afar. Figure 5.5 shows the view on a Chinese street one morning in April 2002.

Photographer Zev Levin said this dust, which arose from a Mongolian Gobi desert storm restricted visibility to half a block.

Even in Seoul, Korea, 750 miles (1207 km) from the origin of a large Chinese sand/dust storm, the effects are major. Author Howard French commented in a *New York Times* article,[6] "It hid Seoul from view throughout the morning, obscuring the sunrise just as surely as the heaviest of fogs. Clinics overflowed with patients complaining of breathing problems, drugstores experienced a run on cough medicines and face masks that supposedly filter the air. Parks and outdoor malls were nearly empty of pedestrians." There are major economic impacts too of a large storm – flight cancellations and worker absenteeism. Manufacturing activities can be interrupted too – the semiconductor industry greatly depends on clean conditions. Such dust storms, "the season of yellow dust," have come regularly to Korea in recent years. French notes that they are "a disturbing reminder for Asians of global interconnectedness and the perils of environmental degradation." In Seoul, the usual level of particulate matter is 70 $\mu g/m^3$. Korean health officials consider that a level of 1000 $\mu g/m^3$ poses serious health threats. However, a recent dust storm from China raised it to 2070 $\mu g/m^3$. The dust also carries arsenic, cadmium, and lead. In spring 2001, the sand storms increased in intensity and frequency with 18 storms on 45 spring days. Japan is increasingly affected, even though it is further away. China has acknowledged the problem and is meeting with Japanese and South Korean officials to discuss prevention.

In China itself, closer to the storm origins, the problem is greater still. The storms originate in China's rapidly expanding Gobi desert. From there, the dust blows across the West Sea and reaches South Korea and Japan. Prolonged drought is responsible for part of the Gobi desertification. But the Chinese Forestry Administration blames about two-thirds of the 2.6 million km^2 desertification on poor agricultural practices and deforestation. According to China's estimates, more than one-quarter of its land area has become desert. The desert, which continues to expand, is now only about 150 miles (241 km) from the capital Beijing. China's State Environmental Protection Administration says 90% of China's usable natural

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[6] French, H. W. China's growing deserts are suffocating Korea. *New York Times*, Section 1, 14 April, 2002, 3.

Figure 5.5 View of a Chinese street during a heavy dust storm. Credit: Dr. Zev Levin, Tel Aviv University

grasslands suffer from varying degrees of degradation. Quite aside from affecting human health and quality of life, desertification affects food production. With its population of 1.3 billion, many believe that China will soon need to import large quantities of grain.

Reducing dust storm severity

What is being done about this critical problem? The Xinhua News Agency says that China has just completed the first 5 years of a process to build another Great Wall – a green wall of trees and grasses skirting 4506 km (2800 miles) around the 350 000 km^2 Taklimakan desert (an area of almost 500 000 km^2). A forestry official said this "gigantic project will alleviate damage from sandstorms to China, slow down the pace of global desertification, reduce the amount of floating dust, and accumulate experience for desert control in China and the world as a whole." They make projections that the buffer zone will reduce wind speeds by as much as 50% and cut sand and dust by as much as 99%. The desert encirclement will take 10 years, and longer-range plans may take 70 years. A side-effect will be the necessity of moving 180 000 people now living in the area near Beijing. The government also plans to impose strict logging bans in the Yellow and Yangtze River watersheds. Local governments not complying with the new rules will lose government funding.

Questions 5.5

1. One Korean official said of the dust storms coming from China, "There is nothing the Koreans can do." How would you respond to his assessment? Explain.
2. Recall the concept of nature's services introduced in Chapter 1. In addition to blocking wind, what services do trees and grass provide?

SECTION IV

Air pollution in less-developed countries

Early in the twenty-first century, the World Health Organization (WHO) attributes 3 million deaths a year to outdoor air pollution. This figure is expected to progressively worsen unless major efforts are taken to reduce air emissions. Cities with worsening pollution are largely found in poor countries. Twelve of the world's most polluted cities are in Asia. Breathing the air in New Delhi is estimated to be equivalent to smoking two packets of cigarettes a day. Burning coal is the major source of air pollution in some less-developed countries, but as the number of motor vehicles increase, they contribute an increasing proportion of the pollution. Across China and India, emissions from coal-burning power plants and industrial facilities contribute to the massive Indian Ocean haze described below. Beijing is one city making a major effort to clean up its air, partially stimulated to do so by the need to be ready for the 2008 Olympic Games. Part of its effort will involve moving highly polluting facilities away from Beijing. But China's effort goes further. As described in Chapter 6, this nation is making a major effort to lower its dependence on coal.

Impacts on children

In megacities[7] and many smaller cities as well, many millions of children in the less-developed world suffer exposure to gross air pollution. In a 1999 publication,[8] Drs. Devra Davis and Paulo Saldiva reported that children in 200 cities are exposed to particulates, nitrogen dioxide, and sulfur dioxide at levels two to eight times greater than the *maximum* that the WHO considers acceptable. Such gross air pollution impairs the respiratory system and lowers resistance to infection. About 80% of all infections induced by pollution in these countries occur in children under 5 years old. One reason that this happens is that young children breathe more rapidly than adults and take in more pollutants; other reasons were discussed in Chapter 3. Air pollution is held responsible too for at least 50 million cases of chronic cough in children under age 14 in less-developed countries. ■ Worldwide, studies carried out by the WHO indicate that particulates have the most serious health effects. Particulate matter accounts for an estimated 460 000 deaths a year and contributes to respiratory disorders in many more. Children at highest risk live in Mexican, Indian, Chinese, Brazilian, and Iranian megacities, but smaller cities can be highly polluted too. And "first-world" children are also sometimes exposed to high pollutant levels. Indeed, some of the highest nitrogen dioxide levels in the world are found in New York, Paris, Tokyo,

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[7] A city with a population of 10 million or more is designated a "megacity".

[8] Davis, D. L. and Saldiva, P. *Urban Air Pollution Risks to Children: A Global Environmental Health Indicator*. Washington, DC: World Resources Institute, 1999.

and Los Angeles. Moreover, the WHO determined that fine particulate pollution causes 7% to 10% of respiratory infections in European children. In the most-polluted European cities, this figure was as high as 21%.

Box 5.9 Massive pollution at sea

During the monsoon months each year, aerosols blow from China and India to the Indian Ocean. They settle there as a brown haze, 3 *km* thick over an area the size of continental United States. This massive pollution results from burning biomass fuels (biofuels including wood, dung, and agricultural wastes), especially in India, and from burning fossil fuels in China and India. Much originates from motor vehicles and other petroleum-based combustion sources in Asian megacities. What is in this haze? Organic chemicals and sulfate top the list followed by black carbon (soot), mineral dust, fly ash, ammonium, potassium, nitrate, sea salt, and desert dust. Carbon monoxide and other gases are also included. Burning biofuels produces an aerosol that contains more soot. Thus, the haze is darker than that seen in Europe or North America. The haze also overlies adjoining land areas of Asia.

The haze reduces the sunlight reaching the ocean by 10% to 15%, probably slowing photosynthesis in ocean plankton. The atmospheric aerosols, with which Western scientists are familiar, cool the immediate environment. However, the sooty haze absorbs sunlight more effectively. It cools the surface beneath it, but warms the atmosphere. ■ This massive blanket of pollution has stimulated a major investigation, the Indian Ocean Experiment, INDOEX. A scientific team uses aircraft, ships, balloons, and two spacecraft (the NASA TERRA and the European ENVISAT), each with specialized instrumentation. Researchers want to improve their understanding of how aerosols of varying composition affect the Earth's climate. They point to continuing population growth in Asia and increasing fuel burning as the cause of the gigantic haze, which they fear could become worse. "Unless international control measures are taken, air pollution . . . will continue to grow into a global plume across the developed and the developing world."

The emphasis of this chapter is outdoor air pollution, which can be dismal. However, indoor air pollution, especially in impoverished countries can be even worse (Chapter 17).

Reducing air pollution

In less-developed countries

Reducing gross pollution is a daunting task. But there are ways to approach even mammoth problems, and steps are being taken. A few illustrations follow.

- Investigators observe that even very poor countries can reduce air pollution. Mexico City, for example, phased out lead in gasoline; and, in the coming decade the World Bank will invest $1.1 billion in this city to promote clean energy and transportation. China and India are of course not oblivious to their environment, and are working to slowly move away from highly polluting coal to natural gas, hydropower, solar and wind energy. Brazil's government promotes less-polluting forms of transportation and energy. A *Global Initiatives* program to reduce air pollution, urges cooperative projects between governments, the private sector, and international organizations to increase energy efficiency.

- A World Bank report[9] states that urban air pollution is a leading cause of premature deaths in Asian cities. To improve air quality, it recommends strategies to reduce emissions from the most commonly used vehicles, those with two-stroke engines. These emit large quantities of fine particulates, and cause an estimated 100 000 to 300 000 premature deaths each year in South Asia. The Bank believes it is not practical to totally ban two-stroke vehicles. Instead, it suggests strategies to induce drivers to use lubricants correctly, and to maintain vehicles regularly to reduce emissions – while also saving money. The report also urges governments to adopt a policy encouraging a switch to less-polluting four-stroke engines.
- China recognizes that its cities have some of the world's worst air pollution, and is working with the UN Development Program (UNDP) to lessen the pollution. Five cities, Beijing, Guangzhou, Xian, Guiyang, and Benxi are implementing UNDP recommendations, and hope that results will set good examples for the rest of China. ■ One UNDP recommendation was to reduce the use of high-sulfur fuel. This would reduce urban air pollution *and* reduce the acid rain impacting crop productivity outside the cities. UNDP urged that fuel prices reflect the true costs of their use including pollution, and that electricity prices reflect the costs of pollution control at power plants. UNDP also called for strong law enforcement to reduce industrial pollution, including expensive fines.
- As part of a 5-year plan, China also pledged, by means of legislation and more investment, to cut gross pollution by 10% by 2005. It believes, however, that environmental protection must be balanced by economic progress to pay for the needed technology.
- An active citizenry is an important means of promoting environmental stewardship. The problems of severe air and water pollution, land degradation, and hazardous waste are too great to leave only to the government. Although small in number compared to Western countries, China has an increasing number of environmental organizations. Previously, if pollution from a factory became unbearable, people might, in the darkness of night destroy it. For this and other reasons, China's government concluded that the better course was to allow legal organizations to promote environmental stewardship. Women's and student groups are also getting involved. At least one Chinese organization takes badly polluting facilities to court, forcing them to compensate those that they harmed. Other

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[9] Kogima, M. and Lovei, M. 2001. Coordinating Transport, Environment, and Energy Policies for Urban Air Quality Management. *World Bank Perspectives*. http://www.giteweb.org/csd/masami.pdf (accessed January, 2004).

organizations collaborate with foreign organizations such as the US Environmental Defense to learn more about tools to help reduce pollution and environmental degradation. Others emphasize environmental education, recycling and conservation. However, it is reported that citizens' organizations must be careful not to offend the government or environmental agencies. ■ For its part, India is reported to have 250 000 citizens' organizations and grassroots movements working on environmental and other issues. ■ Citizens in an increasing number of other countries are also becoming more involved in environmental action. However, in countries with corrupt governments, citizens taking action place themselves in danger of retaliation.

Reducing pollution in Eastern Europe

An outside source of motivation sometimes stimulates environmental clean-up. Many Eastern European countries want to join the European Union (EU). However, to do so, they must have environmental laws equivalent to EU countries. The "Black Triangle" is a region overlapping the borders of Poland, the Czech Republic, and Germany. Its notorious air pollution led to the name "Black Triangle." These countries began reducing emissions in various ways including shutting down many old factories and power plants. Between 1989 and 1999 sulfur dioxide emissions decreased by 92%, nitrogen oxide emissions by 80%, and total particulates by 96%. This happened at the same time as road traffic greatly increased. The region now has air quality comparable to the rest of the European Union.

Reducing transboundary pollution

International treaties and agreements partially control transboundary air pollution.

- Canada and the United States have agreements on a number of shared pollutants. Limiting movement of acid rain pollutants between the two countries is one of these.
- Many treaties are developed under the aegis of the UN Environmental Program (UNEP). European countries adopted a protocol in 1999 (part of the Convention on Long-Range Transboundary Air Pollution) expected to result in major emission cuts for sulfur dioxide, nitrogen oxides, VOCs, and ammonia by 2010. The 15 EU countries typically have strict emission standards. Additional countries joining the European Union must meet the same standards, so increasing the area within which pollutants are well controlled.
- Many other nations are also parties to environmental treaties. The most recent, the Persistant Organic Pollutants (POPs) treaty, bans or severely limits 12 persistent, bioaccumulative, and toxic organic pollutants. Others agreements include the Montreal Protocol on substances responsible for depleting the stratospheric-ozone layer, and the Kyoto Protocol to reduce greenhouse gases. Some treaties

provide technical assistance and money to poor countries to enable them to live up to the agreements.

- As time passes, the international community must deal with increasingly complex issues. Think about the implications if the dense layer of pollution overlying the Indian Ocean continues to spread, or if the international dust storms discussed above worsen.

Questions 5.6

1. Because pollutants can be transported into a country, future policy makers may need (depending on how much pollutant is imported) to set different ambient air standards for different locales rather than using one nationwide standard. (a) What else should countries do if pollution at distant sites continues to worsen? (b) What responsibility does an impoverished nation have to control pollution originating within its borders? (c) What responsibility do wealthy nations have to assist them?

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[10] The UN Wire contains the UN Wire Archives. The archives can be searched by date; in these Internet resources listings this date is shown in parentheses after the web site titles.

Chapter 6

Acidic deposition

"A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise."

(Aldo Leopold)

David Nyhan of the *Boston Globe* described how air pollution is linked to *global* change, "Wind, rain and radioactivity do not stop at the border for passport control, but go where they will. Pollution? Coming soon to a place near you . . . We're all down-winders now." You have already encountered traveling pollutants in this text: radioactive substances from the Chernobyl explosion, persistent organic pollutants traveling to the Arctic, mammoth dust storms from Africa and Asia reaching North America, and smoke from giant fires. This chapter focuses on another major category of traveling pollutants: acidic substances and their precursors. It asks what happens after acids deposit from air onto Earth and water, as happens in many regions around the world. In this chapter, **Section I** identifies the major pollutants responsible for acid deposition, and describes how they are formed. It overviews a half-a-billion-dollar study carried out in the United States to better understand acid deposition. **Section II** examines the adverse effects of acid deposition on water and aquatic life, and on forests and their soils. **Section III** looks at emission sources of acid-forming pollutants, and how to reduce emissions. **Section IV** moves on to international issues around the subject of acid deposition.

Box 6.1 Atmospheric deposition

Atmospheric deposition is a phenomenon in which airborne chemicals or particles – be they acids, metals, organic chemicals, microbes, or pollens – are deposited from air onto land and water. Acids are among the many atmospheric pollutants deposited. Rain can wash them out, and particulate pollutants can settle out during dry conditions. An example follows. There is no record that DDT or PCBs were used in the forests of New Hampshire, but both are found in soils there, presumably airborne from other locations. Supporting this interpretation is the fact that their concentrations are higher at higher elevations than lower elevations, especially on slopes facing the prevailing winds. The amounts deposited do not appear to threaten forest health. Unfortunately, and this is often true of acid deposition, damaging quantities of air pollutants can be deposited around the world.

SECTION I

Acid pollutants

Sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are the major precursors of acid deposition. After emission, these gases react with oxygen in the atmosphere to form acid chemicals – recall Figures 5.2 and 5.3. Then examine Figure 6.1 for man-made and natural sources of acid precursors, their transport and transformation and, finally their precipitation and deposition onto soil and water. Sunlight increases the rate of transformation. ■ If moisture is present, these gases convert to sulfuric and nitric acids, which deposit in rain, snow, and fog. Sometimes acidic fog directly contacts trees growing at high elevations or in coastal regions. ■ In dry conditions, sulfur dioxide and nitrogen oxides are converted to sulfate and nitrate, which slowly settle out by gravity. About half of acid deposition is dry. Dry deposition is more likely to settle near emission sources. ■ In minor amounts other chemicals contribute to acid deposition. Carbon dioxide in a moist atmosphere can convert to carbonic acid. Small amounts of organic acids, such as formic and acetic acids, may be present in the atmosphere too, emitted by natural processes and industrial activity. But sulfur dioxide and nitrogen oxides present the major problem.

Background

Acid deposition was first described in 1852. In the first half of the twentieth century, severe damage to trees and vegetation was seen near smelters,[1] which often release large quantities of sulfur dioxide from sulfur-rich metal ores. Sulfur dioxide emissions from electric power plants burning sulfur-containing fossil fuels also sometimes damaged local vegetation and water. To protect local communities, the 1970 US Clean Air Act required power plants and smelters to build emission stacks 1000 ft (305 m) above ground level. The expectation was that pollutants released at this height would become so diluted in the atmosphere that they would cause no harm anywhere. After the high stacks were built, local damage did abate, but a different problem began to slowly emerge: stack emissions of sulfur dioxide and nitrogen oxides are carried away by the wind for hundreds, sometimes many hundreds, of miles. But, in the meantime, these

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[1] A smelter is a facility that melts or fuses ores that contain metals in order to separate out the metals that the ores contain.

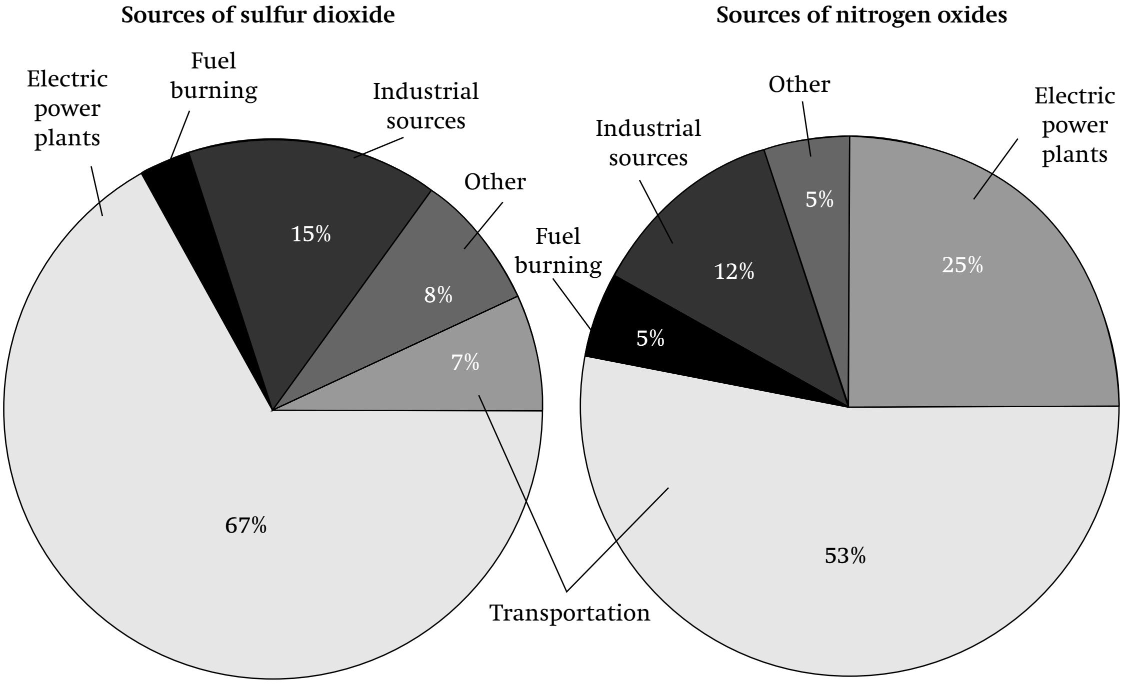


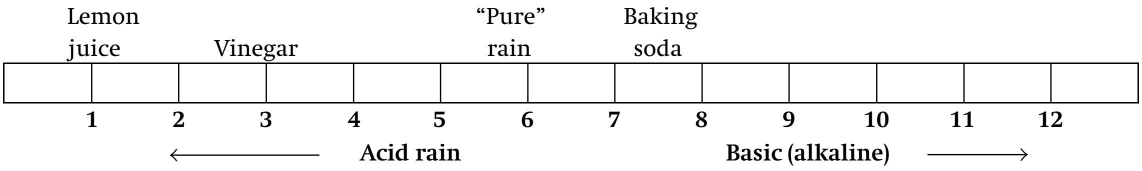
Figure 6.1 Sources of pollutants that form acid deposition

gases are converted to acid aerosols in the atmosphere. The aerosols rain out or settle out onto land, water, and onto man-made materials too. Compared to points of emission, these pollutants are greatly diluted. Also, some alkaline soils continue to neutralize acid deposition over long periods. However, some naturally acidic or only weakly alkaline soils have limited power to buffer the acid. Thus, the soil acidifies and the acid also runs off into nearby streams and lakes. Acid deposition is also stored in winter snow until spring snow melt when it soaks into soil and runs off into water bodies. Acid also falls directly into water bodies. To obtain a sense of the meaning of acidic and pH, and how a pH that is acid can affect aquatic life, see Box 6.2 and Figure 6.2. Between acid runoff and acid deposition from air, water can become acidic enough to harm or kill fish and other aquatic organisms (Figure 6.2). And, as first seen in Norway and Germany in the 1960s, forest growth may begin to decline and trees may die.

Box 6.2

The term "pH" refers to how acid or how alkaline (basic) a solution is. A pH of 7 is neutral. As pH increases above 7, a solution is increasingly alkaline. As pH decreases below 7, it is increasingly acid. The pH scale is logarithmic, so each pH unit represents a ten-fold change: a pH of 5 is 10 times more acid than a pH of 6. A pH of 4 is 100 times more acid than a pH of 6. The only water that has a neutral pH is distilled water, or water that has undergone reverse osmosis; in these cases all other chemicals have been removed to leave pure water.

pH	Effect on life in water
7	Seven is a neutral pH
6	Snails and crayfish begin to die
5	Fish eggs do not hatch. Some fish die
4.5–5	Fish species such as bass and trout begin to die
4	May flies and frogs begin to die



Because of naturally occurring acids in the atmosphere, the pH of rain is less than 7. However, a pH below 5.6 is believed to indicate the influence of human activities. Since 1965, the average annual pH of rain and snow in the northeastern United States has been pH 4.05 to 4.4, well below 5.6. Most of the United States east of the Mississippi River, including the southeast, experiences acid rain to varying degrees. In a few cases, rain has been measured with a pH as low as that of vinegar, about 3, and even as acidic as lemon juice.

Figure 6.2 How acid is acid rain?

The US government spent half-a-billion dollars in the 1980s on the National Acid Precipitation Assessment Program (NAPAP). Teams of scientists throughout the country carried out this ambitious study. Its goal was to understand acid deposition and its effects. Many factors complicated their studies: ■ Rain does not have a "normal" pH; acidic and alkaline substances are naturally present in air and affect the pH of rain to degrees that vary with local conditions. Rain in the eastern United States is often naturally acidic. ■ The pH of lakes and streams also varies. Some are naturally acidic. Thus, it is important to know the historical pH. ■ It was difficult too for investigators to decide whether acid rain was adversely affecting forests because many stresses affect trees in addition to acid deposition. Among these are drought, temperature extremes in winter and summer, insufficient nutrients in the soil, insect attacks, and fungal infections. Ground-level ozone can have a major effect. Researchers struggled with the question of whether acid deposition was harming forests above and beyond other stresses. ■ In 1990, after 10 years of study, NAPAP investigators reported that acid deposition did have demonstrated adverse effects. Additional information was gleaned in the years after 1990.

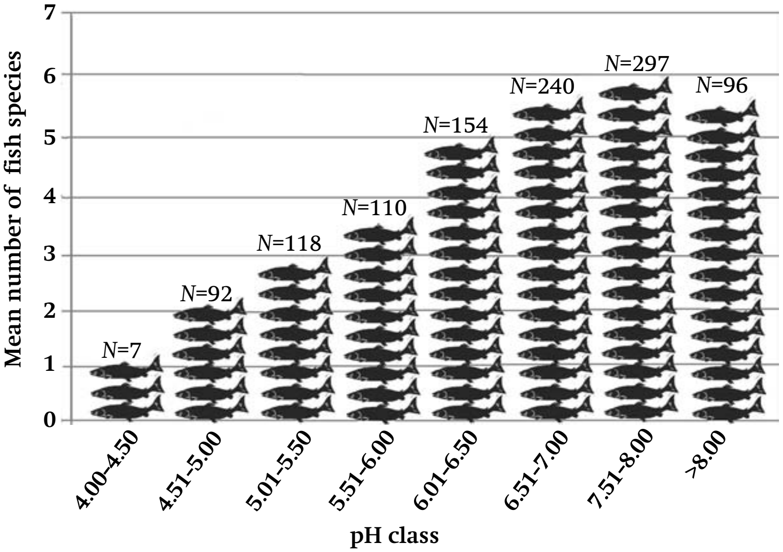
SECTION II

Adverse effects

Water and aquatic life

In 1990, NAPAP reported that acid deposition had caused some US surface waters to acidify. Fish and other aquatic life, including snails

Figure 6.3 Number of fish species able to live at different pH ranges. Reprinted courtesy of Hubbard Brook Research Foundation



and crustaceans, had been adversely affected in 15% of New England's lakes. New York's Adirondack lakes suffered most. More than 40% of the lakes were chronically or episodically acid, and many had no or few fish. As a water body becomes progressively more acid, individual fish may die, fish numbers decrease, and the number of fish species is reduced. Surviving fish may be smaller and less able to cope. Fish are especially stressed if excess aluminum is also present. ■ In 2003, acid deposition continues to harm water quality, making it less habitable to fish and other aquatic organisms. Acid also solubilizes the aluminum in soil, freeing it to run off into water bodies and decrease their pH to potentially toxic levels. ■ In post-1990 studies, investigators looked at the number of fish species living in each of 1469 Adirondack lakes. No fish at all lived in 346 of the most acidic lakes, lakes that also had higher aluminum levels. In the other 1114 lakes, the lower the pH of the lake, the lower the number of species found. In Figure 6.3, the number of lakes at each pH range, *N*, is shown at the top of the column of fish.

Forests and their soils

Forests suffer dieback and decline every 50 to 200 years; this occurs due to a combination of stress and old age. Air pollution adds to natural stress. Forests are damaged not only by acid deposition, but also by ground-level ozone and heavy-metal pollution. ■ In the 1980s, NAPAP researchers saw that red spruce trees growing at high elevations in the northeastern United States were in direct contact with acidic clouds; these trees showed a reduced tolerance to winter cold. They concluded that this damage was the only clear adverse effect of acid on forests, and that some tree kills, previously blamed on acid rain were caused by disease. ■ Even then some scientists objected, saying that even if disease was the immediate cause of death, acid deposition may have left trees vulnerable to disease. Diseased trees may take many years to die. The 10-year NAPAP study may have been too short. Analogous to chronic diseases in humans, adverse effects in trees also may not show up for many years. ■ Moreover, acid deposition continued to fall after the 1990 report. And remember that the sulfur- and nitrogen-containing acids are inorganic. Inorganic chemicals are persistent. They continue to accumulate in soils and waters.[2]

How acid causes damage

A 1996 *Science* article (see Driscoll *et al.* 2000 in Further reading) described serious damage due to acid deposition in the Hubbard Brook Experimental Forest in New Hampshire. Data had been collected on this forest for more than 30 years, but not analyzed until the mid-1990s. Analysis showed that the level of organically bound calcium – a nutrient – in forest soil was only half of its 1960s level. Meanwhile, by 1987, this forest stopped growing. Suspicion as to the cause centered on the lost calcium. Acid deposition can deplete calcium and another nutrient, magnesium, in the following way. Acid begins to solubilize the nutrients allowing them to wash away with rain or melting snow runoff. Rock weathering can replace calcium and magnesium loss, but that takes many years. Meanwhile more acid deposition promotes more calcium loss. ■ To make the problem even worse, calcium and magnesium are not just nutrients. They are "base cations" (alkaline chemicals) that help neutralize the acid. Losing these means an even more acidic soil. ■ Acid causes another ill-effect too. The soil aluminum, which it solubilizes, can interfere with the trees' uptake of calcium and magnesium. And when it runs off into water bodies, aluminum can poison aquatic life if present at high-enough levels.

Think further. The release of acid precursors has only been lowered not stopped, so more acid continues to fall over time. Soils in the northeastern United States including those in New Hampshire are often acidic or poorly buffered. The fact that the first ill-effects of acid deposition described within the United States were in the Hubbard Forest region was thus not surprising. However, as acid deposition continues over time, soils basic enough to have previously buffered the acid also begin to acidify. The better-buffered soils, such as those in the southeastern United States, have only recently become acid saturated; acid has begun to run off into lakes and streams in these areas and concurrently, fish have begun to decline too.

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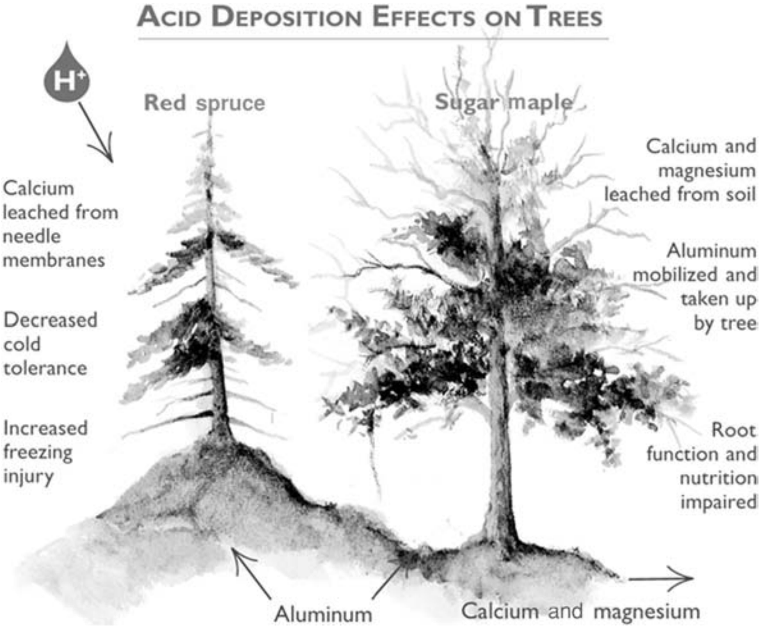
[2] Sulfur and nitrogen can also be plant nutrients. This can complicate the picture because acid deposition may promote the growth of plants and trees growing in sulfur- and nitrogen-poor soil. As with other nutrients, it is an excess that causes problems (Figure 3.2). Smaller amounts may be beneficial – this is especially the case for nutrients.

Figure 6.4 Effects of acid deposition on trees. Reprinted courtesy of Hubbard Brook Research Foundation



Examine what can happen to trees as acid deposition continues to fall over time (Figure 6.4). Notice the loss of needles from the spruce and the loss of foliage from the sugar maple; the trees are also more readily damaged by cold weather. The H^+ shown in the “raindrop” is the acid hydrogen ion. As the soil becomes acid, the essential nutrients (calcium and magnesium) can dissolve from soil, and be lost to rain runoff (as indicated by the lower-right arrow). Acid can also dissolve too much aluminum from the soil; when the trees take up an abnormal amount of aluminum, this too can cause damage.

Other effects of acid deposition

■ Acid deposition can strikingly increase the erosion rate of stone and metal structures. Some European monuments have been badly damaged, as have some stained-glass windows and other cultural resources. ■ Acid aerosols produce hazes that reduce visibility, sometimes obviously. ■ Chapter 5 has discussed the adverse health effects of tiny aerosols on humans.

SECTION III

Sources of acid precursors

We must consider sources of both SO_2 and NO_x as both are major acid precursors. Coal-burning electric power plants are a major source of SO_2 and NO_x in many locales in the United States and worldwide. To lesser extents petroleum-fired power plants also emit SO_2 and NO_x. And remember that motor vehicles are a major NO_x source (see other SO_2 and NO_x sources in Chapter 5). In the United States, SO_2 and NO_x from large coal-burning power plants in mid-western states are blown with prevailing northeasterly winds to New York and New England, and also to Canada. To a lesser extent, acid pollution moves from Canada into the United States. And acid pollutants from Eastern Europe are transported into Scandinavia, and from China to Korea and Japan.

Reducing acid precursor emissions

Sulfur dioxide

SO_2 emissions peaked in the United States at 32 million short tons (28.9 million tonnes; 2000 lbs per short ton) in 1973. With increasingly strict controls mandated by the first Clean Air Act passed in 1970, emissions fell to about 20 million tons (18.1 million tonnes) by 1998. If expectations from the 1990 Clean Air Act Amendments are met, emissions should fall to 15 million tons (13.6 million tonnes) in 2010. ■ Power plants can cut SO_2 emissions in several ways. One is to burn coal with low sulfur content. Also, effective technologies exist to capture the SO_2 formed. A different type of legislative tool, emissions trading, uses market incentives: an individual utility has a SO_2 emission allowance. If it emits less than its allowance, it can sell the unused portion to a utility emitting more than its allowance. Therefore, a facility unable or unwilling to reduce its emissions for whatever reason buys emission rights from a low-emissions facility. Facilities selling thus make money, those buying also believe it is to their financial advantage, and pollution is cut overall.

Reductions in SO_2 were noticed by 1993. The US Geological Survey reported that, at 9 of 33 sites monitored, precipitation was less acidic than in 1980. Sulfate was down at 26 sites. But the pH of rain in US northeastern states remained acid, with a pH of 4.4 in 1997, about ten times more acid than background pH. Acid aerosols continue to lower visibility in US national parks and in many locales around the world; acid deposition is also a continuing problem (see below). In 2002, EU countries began making further cuts in their emissions of SO_2 and NO_x too. China too has begun to lower SO_2 emissions. In one project, China is cooperating with Environmental Defense, a US environmental organization to cut SO_2 emissions from coal burning. China is also beginning to train environmental officials in the emission-trading methods described above.

Nitrogen oxides

NO_x is harder to control than SO_2, which is formed from sulfur present in the fuel. NO_x is formed differently, by a reaction between atmospheric oxygen and nitrogen at high temperatures.[3] This is frustrating because it is high temperatures that otherwise increase the efficiency of combustion. The US Clean Air Act emphasized reducing SO_2 emissions, while doing little about NO_x. Emissions of NO_x peaked at about 25 million tons (22.7 million tonnes) in 1990, and were still 24 million tons (21.8 million tonnes) in 1998. The 1990 CAA Amendments called only for an additional 2 million tons (1.8 million tonnes) reduction. ■ Motor vehicles emit more NO_x than do power plants, but the US Congress has not increased the fuel efficiency of the nation's car fleet. NO_x remains a major pollutant: it contributes to ground-level ozone (described in Chapter 5), it is an acid deposition precursor, and contributes to the pollution of waterways with reactive nitrogen. Meanwhile, as the population grows, the number of motor vehicles grows too along with the increasing miles each vehicle is driven. Because motor vehicles are the major NO_x source, emissions may increase not decrease.

The need for further cuts

Many scientists believe that existing curbs on SO_2 and NO_x emissions in the United States will permit only very slow recovery in the most acid-sensitive environments such as Hubbard Brook. It could take 50 to 70 years for fish and other aquatic life to recover. On the basis of past results and future projections, these scientists believe that the US Congress needs to cut SO_2 from coal-burning power plants by another 80%. This is unlikely to happen in the near future. Even if it did, the most sensitive environments could take 20 to 25 years to recover. Meanwhile, although further cuts in NO_x emissions are slated, NO_x continues to cause damage. Effects in some locations may be irreversible. The situation may become much worse in parts of the world that have poor controls on emissions of acid precursors.

Questions 6.1

When answering questions 1 to 4, recall the toxicology concepts in Chapter 3. Think about how interacting factors – chemicals and otherwise – can cause adverse effects.

1. The sugar maple example described here may remind you of human and animal examples described earlier; name at least one analogy between a toxic effect on a human (or other animal) and what happens in trees. Explain.
2. Explain how reactive (bioavailable) nitrogen, which is essential to plant life, can have adverse effects on growing trees.

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[3] Atmospheric nitrogen is divalent nitrogen, N_2, a very stable chemical. To serve as a plant nutrient, nitrogen must be "fixed" into a nitrogen oxide compound, or into ammonia or an organic chemical. In this text the term "reactive nitrogen" will be used to mean fixed nitrogen, i.e., nutrient nitrogen (nitrogen in a form that is bioavailable to plants).

3. Explain the following statement made by Professor William Smith of Yale's School of Forestry and Environmental Studies: "The integrity, productivity, and value of forest and other wild systems are intimately linked to air quality. We must elevate considerations of environmental health to the same level as concerns for human health."
4. Look at Table 2.1 again. See that in 1990 the US EPA's Science Advisory Panel rated acid deposition as a medium environmental risk (as opposed to a high or low risk). Consider the additional information now available. How would you now rate acid deposition? Explain.

SECTION IV

The international picture

Europe

Damage was more severe in Central and Eastern Europe than in the United States with waters and soils suffering more than three times greater acidification. Forest death was more obvious too. In at least one locale, a German study indicated that the reactive (bioavailable) nitrogen in acid deposition was a greater problem than sulfur. Reactive nitrogen is often the limiting factor in tree growth with trees absorbing and using all they receive. However, as acid deposition continued over the years, the trees could not use all the reactive nitrogen. Many believe that excess reactive nitrogen in forest soil was responsible for the forest deaths seen in Germany. Their explanation follows. Trees responded to the reactive nitrogen in acid deposition by growing faster than usual. Rapid growth further weakened trees already weakened by ozone and other pollutants. The trees eventually became unable to handle natural stresses such as weather extremes or insect attacks. A situation similar to that at Hubbard Brook occurred with excess acid leaching calcium and magnesium from the soil and then being carried off by rainwater. A vicious circle begins. As the alkaline calcium and magnesium are lost, soils are progressively less able to neutralize acid deposition, and tree roots are damaged. This study is relevant to the United States too where until recently, sulfur in acid deposition was the major concern. As sulfur dioxide emissions are controlled, albeit imperfectly, the less well controlled nitrogen oxides pose increasing concerns.

Past agreements among European countries to curb sulfur dioxide and nitrogen oxide emissions led to significant emissions cuts. One approach used was to burn a fuel with lower amounts of sulfur, natural gas. However, actions taken were insufficient, and acid deposition continues to harm forests, fish, and monuments. In late 1999, European countries agreed to further cuts, not only of sulfur dioxide and nitrogen oxides, but also of ammonia and VOCs. Nitrogen oxide emissions are to be cut by 40% by 2010. ■ Some member countries of the European Union, such as Norway and Sweden, are harmed by the transport of acid deposition blown to them from Poland and Bulgaria. These latter two countries are among the Central and Eastern European nations that want to join the European Union. To become members, they must abide by EU environmental regulations, and Scandinavian countries will be less troubled by their emissions. Moreover, with each new country that enters the European Union, its borders are enlarged, thus controlling pollution over a larger area. With increasing control, acid deposition in European countries is expected to decrease in the coming years.

Asia

Recall the smog blanketing the Indian Ocean during monsoon months (Chapter 5). In the summer, the smog blows back over India and China, and it falls as acid deposition, damaging the wheat crop in both countries. In 2002, 200 scientists reported, after a 7-year study, that less solar radiation was reaching the Earth due to this smog; this has a negative impact on the growth of crops and other plant life. It has other effects too, altering rainfall and affecting human health by increasing the incidence of respiratory diseases. Klaus Toepfer, Director of the UN Environmental Program commented on the smog blanket, "There are also global implications, not least because a pollution parcel like this, which stretches 3 km high, can travel halfway around the globe in a week." These worldwide ramifications are being actively studied.

In 2002, China mined more coal than any other country. Coal burning furnishes 80% of its electricity – and 90% of its sulfur dioxide. Acid deposition already damages surface water, soils, ecosystems, and food crops over one-third of China's land area; however, the effects are not yet as bad as those seen in Europe and parts of North America. Yet analysts believe that acid deposition will cause increasingly serious effects unless China and other Asian countries reduce sulfur dioxide and nitrogen oxide emissions. China understands this and is changing the way in which it uses coal. It is reducing subsidies for coal production, and shutting down some heavily polluting industries. Its reliance on coal had fallen 17% by 1999, and it intends further cuts. More recently, China began requiring electric power plants and large industrial facilities to start capturing part of their sulfur dioxide emissions. They intend to reduce sulfur dioxide emissions 10% by 2005, as compared with levels in 2000. The government is also asking households to switch to gas or electricity when possible or to use lime-containing coal briquettes that capture sulfur dioxide. Not only does China suffer from its emissions of acid precursors, but Korea and Japan complain about the pollution reaching them from China. Eleven Asian nations including China are working with the United Nations on means to lower emissions. One early step was to set up an acid-deposition monitoring network in India, Thailand, and Nepal. Local people, trained to measure acidity, operate monitoring stations. Other less-developed countries are also working together to assess the effects of acid deposition, how to lower acid emissions, and how to lower the transboundary movement of a country's emissions into other nations.

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Chapter 7

Global climate change

"We are undertaking a vast experiment with Earth's climate. We're not doing it to test a hypothesis . . . We're doing it because we can't help it. But since we are doing it, we can at least start behaving like good experimenters."

Donald Kennedy, Science Editor-in-Chief

Climate change is nothing new. About 18 000 years ago, Earth was experiencing the last of many ice ages, from which it only emerged about 10 000 years ago. More recently, between the years 1430 and 1850, portions of the Earth passed through a little ice age. The role of greenhouse gases, especially carbon dioxide and water vapor, in warming the Earth is also ancient, and indeed has long served life on Earth well. Figure 7.1 shows a representation of this phenomenon. Radiation from the sun reaches and warms the Earth's surface. In turn, Earth emits radiant heat (infrared radiation) back toward space; part of this radiant heat is captured by water vapor and greenhouse gases. Without this so-called "greenhouse effect" to trap the warmth, the Earth could be 35 °C colder than it actually is, and would not support life. However, the twentieth century has brought greater warming beyond that just described. It is this accelerated warming that we examine in this chapter.

Section I notes that Earth has warmed over the twentieth century. It looks at increased levels of greenhouse gases believed to be responsible for the warming, and examines observations that are consistent with warming including increasing ocean temperature, melting snow and ice, and rising sea levels. **Section II** summarizes how global climate change is assessed using general circulation models. It looks too at the conclusion of the Intergovernmental Panel on Climate Change that the warming is due to human actions. The question is also posed as to whether it matters if the Earth warms. **Section III** overviews the greenhouse gases and their sources. It examines the

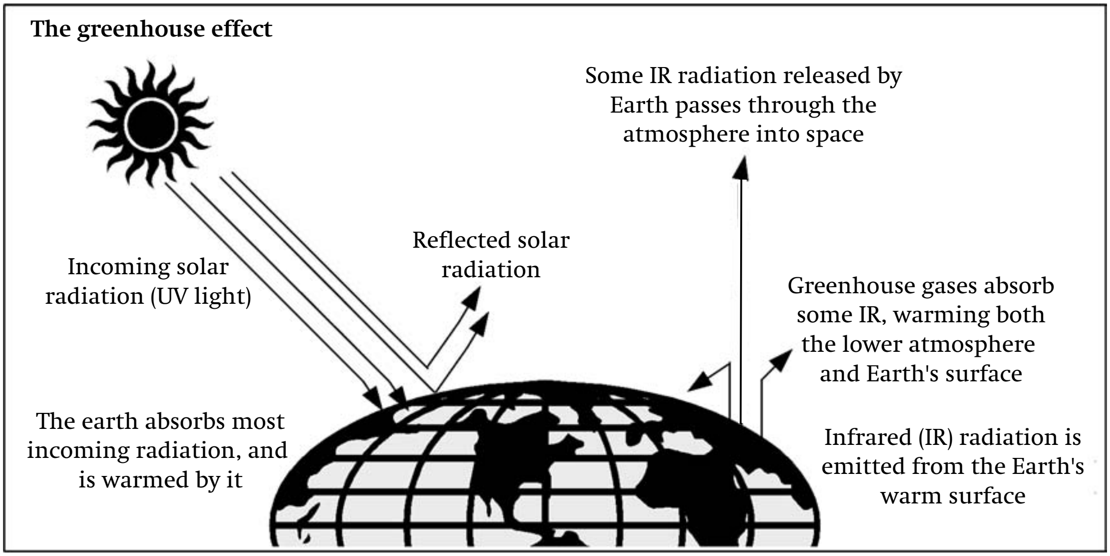

Figure 7.1 The greenhouse effect. Source: EPA (http://www.epa.gov/globalwarming/climate/)

Kyoto Protocol, an international agreement to reduce greenhouse gas emissions, and how emissions can be cut. **Section IV** asks the question of how we can adapt to warming. How might we sequester carbon dioxide away from the atmosphere? It looks too at actions taken to reduce emissions by industries, states, and cities. Finally this section examines the efforts of some less-developed countries to reduce emissions.

SECTION I

A warming Earth

A large number of temperature measurements indicate that the Earth's average surface temperature rose about 0.75 °C (about 1.3 °F) compared with the early twentieth century. The increase has not been smooth (Figure 7.2). It warmed noticeably from about 1910 to the mid-1940s, leveled off, and began increasing again in the late 1970s. The 1990s were warmest of all, and 1998 was the warmest year. The year 2001 was the second warmest with an average temperature of 14.3 °C (57.8 °F), a result arrived at on the basis of 14 000 land and sea measurements around the world. About two-thirds of the century's warming has occurred in the past 25 years. In earlier years, temperature measurements were made in unsystematic locations around the globe. For this and other reasons, there were problems in interpreting the data. One major complication in trying to determine the reality of warming is the "heat island" effect. Many recording stations were in locales where cities subsequently grew up. A city, with its paving and buildings absorbs more heat than a rural area, sometimes

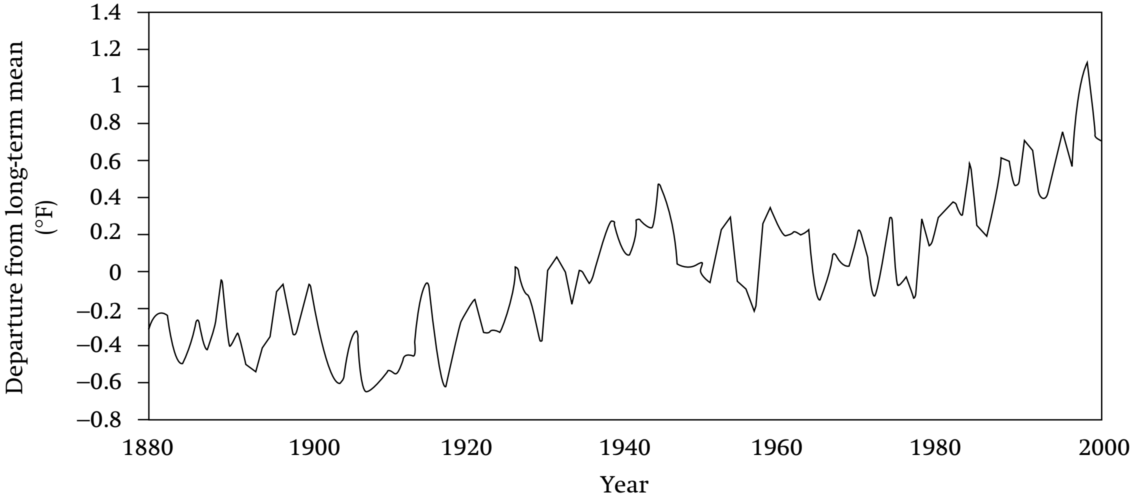

Figure 7.2 Global temperature change (1880 to 2000). Source: US National Climatic Data Center (2001)

dramatically more. Thus, rising temperatures were to be expected in these locations. In the intensive research of recent years, temperatures were also calculated from tree rings, ice cores, other historical data and other means. The results of several research groups using a number of different methods consistently point to a temperature increase this past century.

A puzzling observation results when two temperature records from 1979 to 1994 are compared. The record shown in Figure 7.2 is surface temperature. The other, not shown, is a satellite record, which shows temperature hardly changing over the 15 years. However, one might expect different records because the satellite is measuring radiation 8 km above the Earth. When issues raised by stratospheric-ozone depletion are included in the global climate change models described below, the two records are in closer alignment.

Increasing atmospheric greenhouse gases

Even if we had not detected an increase in temperature, we would suspect one to occur. This is because of the increasing levels of greenhouse gases in the atmosphere, especially carbon dioxide (CO_2), which absorb and trap infrared radiation from the earth. In an 1896 publication, Swedish chemist Svante Arrhenius stated that the climate would warm as we increased the amount of atmospheric CO_2 by burning coal: “We are evaporating our coal mines into the air.” Living in a very cold climate, Arrhenius apparently relished the possibility. Table 7.1 indicates the growth in greenhouse gas concentrations in the atmosphere as compared with historic levels. A striking record of increasing CO_2 concentration is seen in Figure 7.3. The see-saw effect in the figure shows Earth’s respiration. In the cold season plants don’t grow, or grow less, so less CO_2 is taken up from the atmosphere. In the warm season the opposite is true. The ability of vegetation to draw down CO_2 is vivid.

Table 7.1 Increasing concentrations of atmospheric greenhouse gases

	Historic level	Current level	Warming potential compared to CO_2	Lifetime in atmosphere (years)
Carbon dioxide (CO_2)	280 ppm	370 ppm[a]	1	5–200
Methane (CH_4)	700 ppb[b]	1720 ppb[a]	23	12
Nitrous oxide (N_2O)	275 ppb	314 ppb[a]	300	114
Ozone (O_3)[c]	—	—	—	Days/weeks
Chlorofluorocarbons (CFCs) and related chemicals	0	ppt levels	4000–8000	5–100
Perfluoromethane, one of the perfluorocarbons (PFCs)	40 ppt	80 ppt	5700	50 000
Sulfur hexafluoride (SF_6)[d]	0.01 ppt	3 ppt	22 000	3200

Table is adapted from T. J. Blasing and S. Jones (http://cdiac.ornl.gov/pns/current_ghg.html)

[a] Values compared to the year of about 1750.

[b] Recall that ppb (parts per billion) is a thousand-fold lower concentration than ppm (parts per million); ppt (parts per trillion) is a million-fold lower than ppm.

[c] Ozone is a greenhouse gas, but for several reasons, it is not important to detail it here.

[d] Additional greenhouse gases other than those shown here exist, detected at tiny levels, but with high warming potentials. Some also have very long lifetimes.

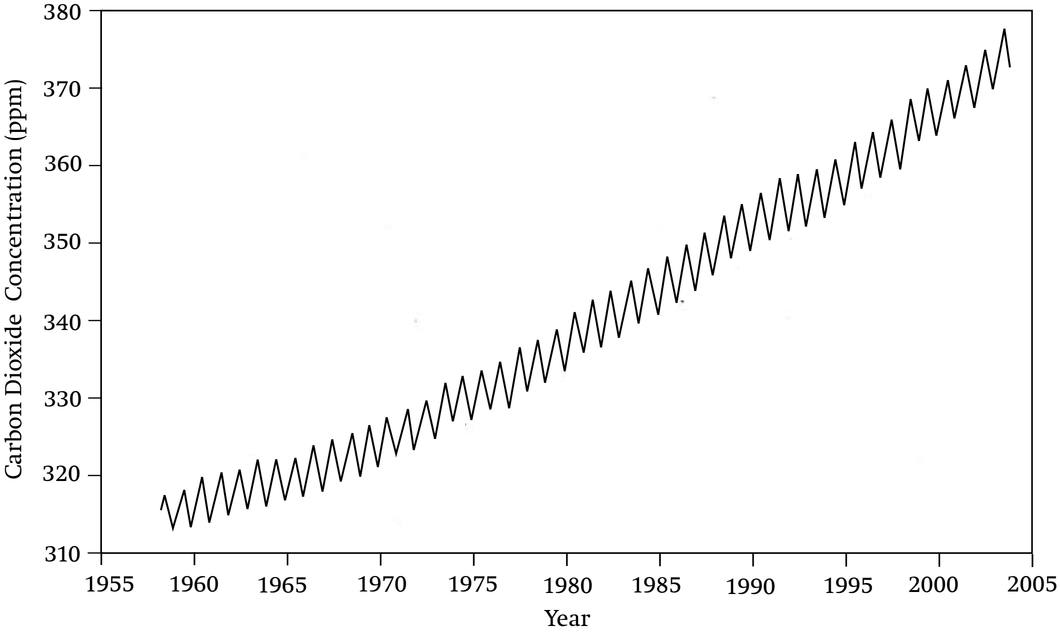

Figure 7.3 Atmospheric carbon dioxide concentrations over time. Source: US National Oceanic and Atmospheric Administration

Box 7.1 | Sunshine and climate change

Variation in the sun's output of radiation may affect climate. The little ice age that lasted until 1850 occurred when solar activity was very low. Recently, researchers have been examining a possible correlation between an 11-year sunspot cycle and Earth's temperature. Between 1958 and 1995, Earth's temperature cycle matched the sunspot cycle. However, 37 years is too short a time to make definite conclusions. Nonetheless, interest in the possible role of the sun in global climate change has been growing. Some calculate that as much as half of the past-century's warming could be accounted for by variations in the sun's energy output, but no one knows. As one researcher phrased it, the sun's true role is ambiguous.

Ice-core studies

Analysis of gas bubbles trapped in Arctic and Antarctic ice dating as far back as 420 000 years tell us that glacial (cold) periods correlate well with low levels of atmospheric CO_2 and interglacial (warm) periods with higher CO_2 levels. In those 420 000 years, atmospheric CO_2 varied only between 180 and 280 ppm. Compare this to the present, when CO_2 is 370 ppm and climbing. One group of scientists commented, "We have left the domain that defined the Earth system for the 420 000 years before the Industrial Revolution." Because few see any immediate hope of stopping our profligate use of fossil fuels, the goal has become to slow the CO_2 increase and to keep it from going beyond about 550 ppm; this is about double the highest level before the industrial age.

Box 7.2 | Information in ice

Ice sheets are laid down one layer of snow at a time, year after year. Similar to tree growth rings, individual years can be discerned although over many thousands of years layers become progressively more distorted as the weight from above of more recent snowfalls increasingly flattens them. Scientists have painstakingly collected ice borings to great depths from Greenland and Antarctica, and analyzed them by a variety of instrumental techniques. The data gleaned tell us what greenhouse gases, other gases, metals and dust were trapped at identifiable times in the past. They also, because of a characteristic of the element oxygen, provide information on temperature. Oxygen has two stable isotopes, ^{16}O and ^{18}O. In warm years more of the heavier isotope ^{18}O is found in air than in cooler years. Thus, core air bubbles tell us how climate cycles waxed and waned over the years. Much other information is also within the ice. The dates that Greeks and Romans most heavily mined lead and copper are laid down in specific layers. So are the years in which large dust storms occurred. Years when nuclear bombs were tested in the atmosphere are also clearly seen by the radioisotopes laid down in the ice. Similar studies can be done with ocean sediment borings, but finer detail is provided by ice borings.

How global warming is showing itself

Increasing ocean temperature

Climate models developed by scientists indicate that the Earth's oceans will warm before the Earth's atmosphere. Previously, there were too few temperature measurements in the ocean to verify this projection. But oceanographers kept looking, and were delighted to recover eventually literally millions of old measurements that had been made by dropping temperature sensors into the sea. Some dated back to the mid-1950s. The information was not systematically recorded, and was stored in many different places and ways. When these data were analyzed they indeed showed the predicted ocean warming. Between 1955 and 1995, both the north and south Pacific Ocean, Atlantic Ocean, and Indian Ocean all showed an average warming of 0.06 °C (0.11 °F) between the surface of the ocean and a depth of 3000 m. A 0.06 °C rise seems small, but think for a moment – if you calculate the volume of three oceans down to 3000 m, the result is a great deal of stored heat. Indeed, researchers at the US National Oceanic and Atmospheric Administration (NOAA) calculated that the oceans were holding ten times more heat to date than the amount that has been used on the Earth's surface to warm the global atmosphere and melt sea ice and glaciers. They noted that the oceans are playing a major heat-trapping role. This is fortunate because it tends "to steady the rest of the climate system."

Just as the Earth's surface temperature did not increase smoothly over time, neither did ocean warming. An increased amount of heat was stored in the years before each temperature rise was detected over land – just as models had projected. A worrisome point is that no one knows how much more heat oceans can store before surface temperatures begin to increase more rapidly. NOAA is setting up a new temperature-monitoring system, "Argo." Argo spans the oceans with 3000 free-floating packages of instruments, which are linked by satellites. Data collected from these will create a "weather map" of the ocean down to 1500 m.

Snow and ice are melting

In the US state of Alaska, the temperature has risen by 3 °C (5.4 °F) in the past 30 years, four times greater than the average global increase. This increasing temperature has led to the melting of Alaskan glaciers at what a University of Alaska research team calls an "incredible rate," much faster than was previously thought. A few glaciers are exceptions in that they have gained mass. Using aircraft-carried laser devices, researchers measured the volume of 67 Alaskan glaciers. They compared this information with aerial photographs taken between the 1950s and the early 1970s, and to contours of US and Canadian topographic maps. They made calculations which yielded a surprising result – the melting Alaskan glaciers have contributed at least 9% of the sea-level rise seen in the twentieth century. Researchers asserted that the glacial melting is faster than anything that has happened in at least ten centuries. However, it isn't only glaciers that are melting. People's lives are affected. Alaska's permafrost (permanently frozen subsoil) is beginning to thaw. This is resulting in sagging roads, sinking pipelines, and rapid multiplication of insects that feed on the state's spruce forest. Some trees are showing their roots as the permafrost melts.

Rapid melting goes far beyond Alaska.

- Africa's highest mountain is in Kenya, Mt. Kilimanjaro with its famous "Snows of Kilamanjaro." As compared with a 1912 survey, 82% of the icecap has melted. If current rates continue, melting will be complete between 2010 and 2020.
- Mountain glaciers in places as far apart as Peru and Tibet are also melting. Figure 7.4 shows Peru's Qori Kalis. This glacier shrank 33 times faster between the years 1998 and 2000 than it did in 1963 to 1978. The bottom photograph of Figure 7.4 shows how much of the glacier had melted and the 10-acre (4 hectare) lake formed from the melt.
- In Nepal and Bhutan, 44 lakes around melting glaciers are filling so quickly that flooding is feared within a few years.
- At the location of the world's highest peak in the Himalayas, people climbing the mountain must now walk 2 hours from base camp before reaching the ice whereas in 1953 Sir Edmund Hillary stepped directly onto ice from the base camp.
- Many other glaciers around the world are melting too, much more rapidly than in earlier years.
- There are exceptions – a small number of glaciers have added mass. Also, the interior of Antarctica has cooled in recent decades. But at the same time, the Antarctic Peninsula warmed so much (2.5 °C, 4.5 °F) over the last 50 years that it lost a Rhode-Island-sized chunk of its ice shelf in 2002.

Sea levels are rising

Globally, sea levels rose 10 to 20 cm (4 to 8 in) in the twentieth century. You can see the eating away of some shorelines that resulted by comparing pictures of lighthouses taken a hundred years ago or more to present pictures in which they are much closer to the water. Today, a space-based technology is used to study these changes. A US–French satellite has been calculating changes in sea levels since 1992. Now a newer satellite, Jason, with better instrumentation continues to assess rising sea levels, especially along low-lying coastlines such as those found in certain island nations, in Bangladesh, and parts of coastlines in other countries. One billion people would face homelessness if the sea rose 1 m. In Bangladesh alone, a 1 m rise would displace 15 to 20 million people. According to a researcher at the United Kingdom's Hadley Climate Centre, "The sea-level rise in the last 100 years was about 10 times faster compared with the average growth over the last 3000 years." Some scientists believe that part of the increased sea level is natural, due perhaps to changes in land movement. Increasing water temperature increases sea level in two

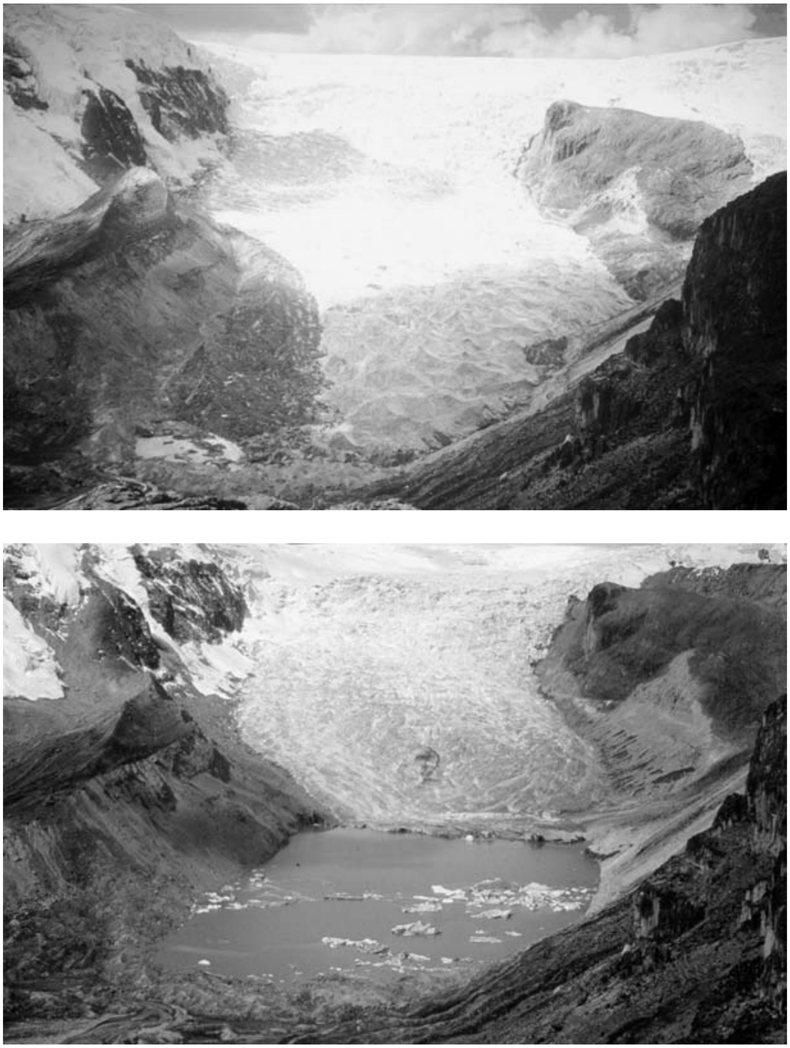

Figure 7.4 Qori Kalis glacier flowing from Peruvian mountains. Top photo, 1978; bottom photo, 2000. Credit: Dr. Lonnie Thompson, Ohio State University

ways: (1) as water warms it expands to take up more space; (2) as ice melts there is an increase in the amount of water in the oceans.

SECTION II

Assessing global climate change

Analysis of change

Each of the issues just discussed was investigated using scientific instrumentation from space, air, Earth, and sea. However, we need a method to pull all this relevant information together into a usable picture that will allow us to see climate holistically, and use it to provide future climate projections. For this, scientists use computer models. *General circulation models* (GCMs) are used to project future climate. These models project a warming of between 1.4 and 5.8 °C (2.5 to

10.4 °F) in the twenty-first century. This wide range in possible temperature increases reflects the different GCMs used, and the information entered into it. There are several complex GCMs, each incorporating somewhat different information on: greenhouse gas characteristics and their sources and environmental sinks; atmospheric and ocean circulation; clouds and aerosols; reflectivity of snow, land, and water; and many other variables. A GCM takes a given set of conditions and makes future projections from them. It projects not just temperatures, but rainfall and snowfall patterns, storm severity, sea level, and more. Some successful projections have been made. GCMs successfully projected the cooling effect on the climate of the eruption of the Philippines' Mt. Pinatubo in 1990, which injected huge quantities of sulfur dioxide and particulates into the atmosphere. They have also had success in reproducing the global warming of the past century. ■ One variable that scientists continue to struggle with is the effect of atmospheric particulates on climate. Sulfate aerosols reflect part of the sunlight back into space and are generally agreed to have a cooling effect. However, soot aerosols may have a net warming, not cooling, effect. ■ Clouds are another uncertainty. High clouds appear to enhance the greenhouse effect, but low clouds reflect incoming sunlight back into space and have a cooling effect. The current net effect of clouds is cooling.

Models are powerful, but cannot give absolute answers. They make projections based on available information. ■ A major limitation of GCMs is that at present, they cannot predict what will happen in any particular small region, such as a state or province. Certain areas may cool not warm, which does not necessarily contradict climate models. A perhaps obvious limiting factor is that GCMs are only as accurate as the information incorporated into them. They must be continuously modified as additional data are gathered. Information remains incomplete. ■ Among projections that all GCMs make is that, once warming begins, it will continue for hundreds of years. This is another reason to take global warming seriously even though uncertainties remain. See web sites such as those in Further reading for additional information.

The Intergovernmental Panel on Climate Change

The IPCC, the Intergovernmental Panel on Climate Change, was formed in 1988 by the World Meteorological Organization and the United Nations. Hundreds of scientists from 178 member nations do exceedingly careful reviews of climate data, and periodically report on their findings. A 1995 report said that there is a "discernible human influence" on global warming. Then, in 2001, after 3 years of further study, an IPCC report went further and attributed most warming of the past 50 years to human activities. Several of their conclusions follow.[1]

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[1] UN Environment Program, Intergovernmental Panel on Climate Change (IPCC). 2001. Third Assessment Report. http://www.ipcc.ch/ (accessed January, 2004).

- Atmospheric greenhouse gases continue to increase as a result of human activities.
- The fraction of warming due to carbon dioxide exceeds 50%.
- Decreases of about 10% in snow cover have occurred since the late 1960s.
- Reductions in the year's duration of lake and river ice cover in the northern hemisphere's mid- and high latitudes occurred in the twentieth century.
- Increases in the heat contained in the world's oceans have occurred since the late 1950s.
- Between 0.1 and 0.2 m rise in global average sea levels occurred in the twentieth century.

IPCC scientists did not believe that variance in solar radiation, natural climate fluctuation, or poor climate models explained the warming. As IPCC Chairman Robert T. Watson said, "We see changes in climate, we believe we humans are involved, and we're projecting future climate changes that will be much more significant in the next 100 years than in the past 100 years." The panel projects that, if current trends continue, increases in atmospheric greenhouse gases in the twenty-first century will result in an average global temperature increase between 1.4 and 5.8 °C (2.5 to 10.4 °F). About 75% of the warming is expected to be due specifically to carbon dioxide. They also project sea-level rises of another 0.1 to 0.9 m. A sober forecast is that climate change will persist for many centuries.

Even the 1995 IPCC report greatly altered the world's view of climate change, and led to the 1997 Kyoto Protocol, an international agreement among industrialized nations to modestly reduce emissions of greenhouse gases. IPCC members willingly admit to many uncertainties about global climate change. Chairman Robert Watson commented, "We could conceivably be overestimating the effect human activities have on the Earth's climate." However, "we could also be underestimating it." As Dr. Donald Kennedy, Editor-in-chief of *Science* said, "We are now undertaking a vast experiment with Earth's climate. We're not doing it to test a hypothesis or achieve a result, and it doesn't have a design. We're doing it because we can't help it. But since we are doing it, we can at least start behaving like good experimenters: collect the data carefully, examine the background factors that have taken us to where we are, and prepare ourselves for mid-course modification in the (Kyoto) protocol if the need for that becomes clear."

Does it matter if the Earth warms?

By the end of the twentieth century Earth's temperature had increased about 0.75 °C (1.3 °F) compared with the pre-industrial age. This seems modest until you consider that an average temperature at the Earth's surface is only 15 °C (59 °F). During the last major ice age, ending about 10 000 years ago, temperatures were only about 5 °C colder than today. And temperature has varied only about 2 °C since then. We noted above that even with a 0.75 °C increase we see warmer oceans, melting ice, and rising sea levels. General circulation models (GCMs) project that, as greenhouse gas levels continue climbing, Earth's average temperature will increase between 1.4 and 5.8 °C (2.5 to 10 °F) in this century. Warming toward the higher end could be devastating. Even an increase of 2 °C would be the highest temperature in the past 2 million years.

Many future changes are projected as temperatures increase.

- Think about the implications of the melting Peruvian glacier Qori Kalis. Dr. Lonnie Thompson of Ohio State University noted that as the glacier melts, "hydroelectric dams and reservoirs in Peru (will) be flush with water." But, as the glacier disappears, what happens to communities that now depend on it for drinking water, agriculture, and electricity? For electricity, they may turn to oil or coal – and produce more greenhouse gases. Many other glaciers around the world are also melting.
- Coastal flooding will increasingly occur with rising sea level. People, who are already poor and overcrowded, may be forced from homes in low-lying countries such as Bangladesh. Prosperous countries such as the Netherlands, long accustomed to fighting back the sea, may lose land too. A rising sea level can exert great damage even in less critically affected regions, e.g., beaches, beach-front property, and may increase storm surges along coastlines. A higher sea level also means salty water can infiltrate fresh groundwater in coastal areas, making it undrinkable. Such infiltration of ocean water can also destroy coastal ecosystems, and the species they support. Inland wetlands and ecosystems are also at risk.
- Rainfall patterns would be altered, with some areas getting more rainfall and others suffering more droughts. Think about soil and trees. On warmer days more water evaporates from these into the air leading to more clouds and rainfall. But moisture can also evaporate from dry soils, depriving them of already limited moisture.
- Storms of increased severity are expected. This happens because trapped heat energy drives atmospheric air circulation and oceanic water circulation. These circulations have been positive forces because they distribute heat energy more evenly around the world – making Earth on average a more moderate place to live. However, hurricanes and typhoons feed on this warmth too, and as the energy in air and water increases, storms can be expected to grow to greater severity than in the past.
- Another logical accompaniment of increased warming is more severe heat waves. Higher temperatures would worsen air quality – recall that photochemical smog increases on hot summer days.
- Diseases currently restricted to existing hot regions may move into the newly warming regions. Malaria is one such disease, spread by mosquito vectors, infecting and killing millions each year in warm climates. As temperature increases in currently temperate regions,

mosquitoes and other insects are expected to move in, spreading diseases as they go. In addition, indigenous disease organisms previously killed by winter cold will be better able to survive milder winters.[2]

- In the oceans, warming damages coral reefs – a marine source of great biodiversity. Coral reefs have limited tolerance for warm waters. They compensate in the short run, but with continued warming, they will die.
- Increased carbon dioxide and warmer temperatures can have positive effects too. Agricultural crops, up to an unknown point are expected to respond with increased growth as the concentration of the nutrient carbon dioxide increases. However, the regions suitable for growing particular crops and trees will change. There are many other potential impacts, some important, in addition to those described here.

SECTION III

Greenhouse gases and their sources

The major greenhouse gas, simply because of the huge quantities produced, is carbon dioxide. Others of importance are methane and nitrous oxide. Chlorofluorocarbons (CFCs) and ozone are also greenhouse gases. Some scientists now call for *soot* to be included in the greenhouse list. All greenhouse gases (or particulates such as soot) are minor atmospheric components, which does not decrease their seriousness. Even the most abundant greenhouse gas, carbon dioxide is only found at about 370 ppm (0.037%). Compare 0.037% to nitrogen's 78.1% and oxygen's 21%; neither nitrogen nor oxygen absorb infrared radiation. Water vapor is the most plentiful greenhouse gas in the atmosphere with a concentration of almost 1%. Global warming skeptics sometimes argue that this is a reason to discount the influence of other greenhouse gases. However, we know that carbon dioxide, methane, nitrous oxide, and other greenhouse gases absorb infrared radiation coming from the Earth, and that their atmospheric levels have increased and continue to increase. And we know that an ice-core record of 420 000 years shows that carbon dioxide was higher during warm periods and lower during cold periods although one must be careful about attributing causality. Moreover, carbon dioxide levels did not increase beyond 280 ppm over those 420 000 years.

Carbon dioxide

CO_2 is the major greenhouse gas accounting for more than 50% of the current warming when all greenhouse gases (excepting water vapor) are added together. CO_2 does not powerfully absorb infrared radiation.

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[2] Diseases are already spreading for other reasons, in particular the massive increases in international trade and travel. The West Nile virus in the United States may be an example of these latter reasons.

However, its concentration at 370 ppm is much higher than other greenhouse gases. It is also persistent, with an atmospheric lifetime of over 100 years. Human activities emit more than 6 billion tons (5.4 billion tones) of CO_2 into the atmosphere each year.

Carbon dioxide sources

Worldwide the major source of CO_2 is fossil-fuel combustion (coal, petroleum, and natural gas), contributing about 80% of anthropogenic CO_2. Coal has the greatest carbon content among fossil fuels, and emits more CO_2 when burned than petroleum does. Natural gas emits the least CO_2. ■ Coal-burning electric power plants are the major CO_2 sources in many countries from the United States to China and India. Petroleum-burning motor vehicles contribute about 25% of the CO_2 in the United States ■ Deforestation contributes too because when felled trees are burned, their stored carbon is released as CO_2. At the same time, deforestation leaves fewer trees to take up atmospheric CO_2. Trees that are grown on a sustainable basis make no net CO_2 contribution. In *sustainable growth*, as much tree biomass is grown as is harvested on an ongoing long-term basis. ■ *Natural CO_2 sources* include releases from oceans and land, and plant respiration. Microbes also release CO_2 as they decompose dead plant and animal matter. Animal respiration releases CO_2 too. Volcanoes are a large natural source.

Carbon dioxide sinks

Oceans are a major CO_2 sink, containing about 50 times more carbon than the atmosphere. *Terrestrial biomass* including trees and grasses store about three times more CO_2 than the atmosphere. Together, ocean and terrestrial ecosystems absorb perhaps half the excess CO_2 generated by human activities. The rest enters the atmosphere increasing its level of this gas. One group of scientists expressed their belief, ". . . natural sinks (oceans and land) can potentially slow the rate of increase in atmospheric CO_2, (but) there is no natural savior waiting to assimilate all the anthropogenic CO_2 in the coming century."

Box 7.3 | Carbon dioxide is more than a greenhouse gas

Only in recent decades have we thought of CO_2, at least the CO_2 in outside air, as a pollutant. After all, CO_2 is vital to life on earth. It is captured through photosynthesis by trees, plants, phytoplankton and some bacteria, and used to make carbohydrates, proteins, and lipids and other biochemicals. Almost all biochemicals derive from fixation of atmospheric CO_2 – including those within plants, and other photosynthetic organisms that trap CO_2 and all the biochemicals within creatures that eat the plants and single-celled organisms. It includes too the hydrocarbons of coal, petroleum, and natural gas, which were once biochemicals. ■ CO_2 is a waste gas respired by animals, plants, and many bacteria. Students sometimes express a belief that an increasing human population breathing out CO_2 is the reason that atmospheric CO_2 levels are increasing. This is not true. (See Internet resources, Frequently Asked Global Change Questions.) The major reason for increased CO_2 is fossil-fuel burning and, secondarily, deforestation. ■ CO_2 is also an acid precursor. In the presence of atmospheric moisture, part is transformed to carbonic acid. CO_2 reaching water bodies is converted into carbonic acid, bicarbonate, and carbonate. Carbonate accumulates in shells and coral, and eventually in ocean sediments. There is concern that, because oceans are such a large sink for CO_2, the pH of ocean water may eventually decrease enough to damage ocean life. This is an area of active investigation.

Methane

Methane (CH_4) is a simple hydrocarbon gas accounting for about 20% of the greenhouse effect. It is second in importance only to carbon dioxide. Its atmospheric concentration is only 1720 ppb or 1.72 ppm. This is a level more than 200 times lower than that of carbon dioxide, *but* molecule for molecule, methane has almost 25 times greater ability to absorb infrared radiation from the Earth than carbon dioxide. Fortunately, it has a much shorter atmospheric lifetime, about 12 years.

Methane sources

Agriculture is a major anthropogenic source of methane. Domestic ruminant animals, especially cattle and sheep, emit about 15% of all methane. Rice paddies produce methane too.[3] ■ Landfills produce almost as much methane as agriculture. The anaerobic bacteria within landfills degrade organic wastes such as food, paper, wood, and plant debris. By themselves American landfills emit an estimated 7% of the world's methane. ■ Other sources are methane leaks during coal mining, and flaring of natural gas from oil wells. ■ *Natural methane sources* include Arctic tundra and wetlands where anaerobic bacteria break down organic material. Tropical termites release methane as a result of their symbiotic relationship with microorganisms; so do millipedes, cockroaches, and scarab beetles. Tropical insects or those living indoors, for instance, cockroaches, produce especially large amounts. The oceans and methane-hydrate deposits in permafrost release methane too. Compared to pre-industrial times, methane's atmospheric levels are high (Table 7.1). However, its atmospheric growth rate has declined by about two-thirds since 1980. No one knows why.

Questions 7.1

1. What does the following statement mean: Sustainably grown trees and other biomass make no net contribution to carbon dioxide?

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[3] This happens because *anaerobic* bacteria (bacteria that do not need oxygen) live in the paddies. These anaerobes break down organic material to methane, not CO_2. (*Aerobic* bacteria use oxygen and break down organic material to CO_2.)

2. The expiration of carbon dioxide by more than 6 billion people on Earth doesn't make a net contribution to atmospheric carbon dioxide. Nonetheless, there is an association between growing population and greenhouse gas emissions. How does a growing human population lead to: (a) Increased carbon dioxide emissions? (b) Increased methane emissions? (c) Increased nitrous oxide emissions?
3. How does increasing industrialization in poor nations increase carbon dioxide emissions disproportionately compared to more-developed countries?
4. Other than reducing greenhouse gas emissions, what are three additional environmental reasons to reduce fossil-fuel use?
5. Trees, especially young rapidly growing trees, serve as an important terrestrial sink for carbon dioxide by taking it up from the atmosphere. What are three other environmental reasons to avoid deforestation?
6. How does lowering petroleum use benefit national security?
7. Review the uncertainties related to global climate change. Are these uncertainties so great that you believe we need not lower greenhouse gas emissions? Explain.
8. Climate warming is expected to increase ground-level air pollution. Why?
9. Think about a college campus. (a) What are two steps it could take to reduce greenhouse gas emissions that would have no cost? (b) What are two steps it could take that will pay for themselves in fuel savings over a short period of time, a short pay-back time?
10. The IPCC uses the word "project" as a verb, e.g., IPCC projects a warming of between 1.4 and 5.8 °C in the twenty-first century. What does it mean by "project?"
11. The IPCC believes that 75% of the warming expected in the twenty-first century will be due to carbon dioxide. What does this tell you about the predominating fuel that we will be burning?
12. Go to the American Forests' web site: http://www.americanforests.org/resources/ccc/. Use the Climate Change Calculator to determine how much your household contributes to atmospheric carbon dioxide. Alternatively, consult the article by Lavendel in Further reading to examine your emissions. (a) What three steps could you take to reduce your personal greenhouse gas emissions? (b) Which steps, if any, are you most likely to take?
13. Why are glaciers sometimes referred to as nature's water towers?

Nitrous oxide

Nitrous oxide (N_2O) accounts for about 5% of the greenhouse effect. Its atmospheric concentration is only 310 ppb, but it has 300 times greater ability to absorb infrared radiation than carbon dioxide does. It has an atmospheric life of over 100 years. ■ A human activity that releases N_2O is soil cultivation, especially adding nitrogen fertilizer. Microbes convert this to other chemicals including N_2O. Fossil-fuel burning in electric power plants and biomass combustion also produce some N_2O, as do nylon and nitric-acid production. ■ The major *natural* N_2O *source* is the bacterial breakdown of reactive nitrogen chemicals in the soil especially in forests (enhanced when humans add reactive nitrogen, fertilizer, to soil). Another natural source is ocean water.

Ozone

Ground-level ozone is a greenhouse gas – it can absorb infrared radiation and contribute to warming. Ground-level ozone forms from VOCs and nitrogen oxides in the presence of heat and the sun's ultraviolet radiation (Chapter 5). In the stratosphere, ozone destruction has a cooling effect offsetting the effect of too much ground-level ozone. However, if stratospheric ozone levels continue to recover as expected, this offsetting effect will become progressively less important.

Other greenhouse gases

The synthetic chemicals, CFCs, are potent greenhouse gases, but the Montreal Protocol has banned CFCs, and they may become insignificant as greenhouse gases. ■ The perfluorocarbons (PFCs) are byproducts of aluminum smelting and are also used in semiconductor manufacture (Table 7.1). ■ Sulfur hexafluoride (SF_6) is used in magnesium smelting and as an insulator in electrical equipment (Table 7.1). ■ Some other industrial chemicals are potential greenhouse gases, but these are under control.

Soot as a greenhouse "gas"

Some scientists proposed in 2001 that soot (black carbon) be added to IPCC's list of greenhouse chemicals. Western scientists had previously been familiar only with North American and European sulfate hazes. These cool the atmosphere by reflecting sunlight back into space, and also (when present in clouds) make clouds more reflective. But the massive Indian Ocean haze (Chapter 5) contains more soot than Western hazes. Soot appears to absorb sunlight and then apparently radiates it. When soot was studied in a computer simulation of climate at Stanford University, results showed that it had a large warming effect. However, soot is not necessarily produced during burning. Efficient combustion could greatly reduce or eliminate its production. Thus, even in less-developed countries it could potentially be well controlled. Soot also has a much shorter atmospheric life than greenhouse gases because it can be rained out of the atmosphere within a week or two.

Reducing greenhouse gas emissions

International agreements

UN Framework Convention on Climate Change

In 1992 at the UN Earth Summit in Rio de Janeiro, many countries signed this convention. Its objective was to stabilize "greenhouse gas concentrations . . . at a level that would prevent dangerous anthropogenic interference with the climate system." Anthropogenic interference means human interference. About 150 countries ratified the convention. By ratifying it, a country was agreeing to return its greenhouse gas emissions to 1990 levels by 2000. In the United States, then President Clinton developed a Climate Change Action Plan to lower greenhouse gas emissions. However, the steps of the plan were voluntary and US emissions, far from decreasing, continued to climb. The same was true of many other countries. This result indicated that stronger measures were needed to reduce greenhouse gas emissions, a plan that clearly specified: (a) the exact reductions in greenhouse gas emissions; and (b) when these reductions were required.

The Kyoto Protocol

After strenuous negotiating sessions, the Kyoto Protocol (also under the UN Framework Convention on Climate Change) was adopted in late 1997. Under the protocol, industrialized countries agreed to reduce greenhouse gas emissions to an average of 5.2% below 1990 levels between the years 2008 and 2012. Nations signing the protocol then labored further to resolve three controversial points. (1) Find acceptable means of accomplishing greenhouse gas reductions. (2) Agree on an accounting system that gave nations credit for their reductions. (3) Agree on penalties for lack of full compliance with agreed-upon reductions. This third point was left until later to resolve.

In July 2001, 1700 diplomats representing 178 countries resolved the first two of these points. Meanwhile, the United States had become only an observer to negotiations because a new President, George W. Bush, refused to consider ratifying this “fatally flawed” document. This made matters difficult for the protocol, because, for it to come into force, 55 countries (accounting for at least 55% of the world’s 1990 emissions) had to ratify it. With the United States – accounting for 25% of the world’s emissions – standing aside, it is difficult to reach 55% although as of 2003, this may still happen. One US objection was that the protocol does not require less-developed countries to reduce their emissions. They were omitted because it is industrialized countries that are largely responsible for current levels of atmospheric greenhouse gases (Figure 7.5). And, industrialized nations are the ones able to develop the technology to lead the way in making reductions.

How to reduce greenhouse gas emissions

Conservation and efficiency

On the basis of earlier chapters, you know that to reduce the quantity of fossil fuel used, society must practice conservation and, at the same time, burn fossil fuels more efficiently (produce more energy per amount used). Measures include encouraging electric utilities to use “co-generation” to allow more of the energy that they produce to be used, and developing more energy-efficient industrial motors and household appliances. Many simpler measures are important too. One is improving appliance circuits so they don’t draw current even after they are turned “off.” Developing more environmentally compatible energy sources is also critical. In addition, because trees sequester carbon we need to prevent further deforestation and promote the planting of additional forests. Other greenhouse gases, such as methane, require different approaches. One method to reduce

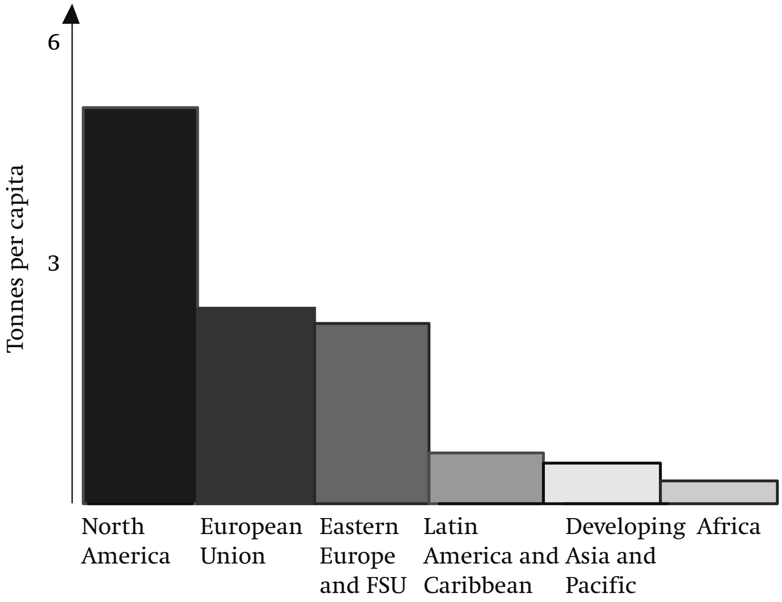

Figure 7.5 Carbon dioxide emissions per capita (year 2000). FSU, former Soviet Union. Source: US Energy Information Administration

methane emissions is to dry out rice paddies when they are not in use. To reduce nitrous oxide emissions, we need to avoid using too much fertilizer on farm crops.

Kyoto Protocol reductions

Parties to the Kyoto Protocol wanted flexibility in how they could pursue reductions in greenhouse gas emissions. They spent great amounts of time discussing *flexibility mechanisms*, ways by which a nation could take credit for reducing emissions. ■ Greenhouse gas trading. A nation (or company) that reduces its greenhouse gas emissions more than required would be allowed to sell its "excess" to another nation (or company) that had not reduced its own emissions so well. That nation (or company) would then receive credit just as if it had made the reduction itself. ■ Joint implementation. Here, a developed country gets credit for cooperative projects that it undertakes with less-developed countries to reduce greenhouse gas emissions in the latter nations. ■ A somewhat different approach is the "clean development mechanism." Here a company or country finances a project in a less-developed country. It may plant a forest in that country to take up atmospheric carbon dioxide. Or it may pay for solar roofs in that country to provide electricity without producing carbon dioxide (unlike an electric power plant burning a fossil fuel). Or, it may help that country build an energy-efficient factory. Flexibility mechanisms are intended to *supplement not replace* direct actions by a country or company such as conserving fossil fuel.

Unfortunately, even assuming that countries fulfill the requirements of the Kyoto Protocol, the reduction in greenhouse gas emissions achieved will be minimal compared with the scope of the problem. The major question remains: What level of greenhouse gases will avoid “dangerous anthropogenic interference” with the climate system?

Reducing population growth

A US National Academy of Sciences report stated that population growth is the major single driver of atmospheric pollution. ■ A growing population leads to growing fossil-fuel use and greater pressure to cut forests. These activities enhance carbon dioxide levels in the atmosphere. ■ A growing population promotes more agricultural activities, more cattle and more rice paddies that enhance methane emissions. ■ In the United States which lacks a population policy, population is growing about 1% a year. Not surprisingly, there has been a concomitant increase in carbon dioxide emissions.

SECTION IV

Industry and government action to reduce emissions

Industry action

Some major industries don’t see global warming as a problem, and have actively opposed the Kyoto Protocol. Others see it differently. BP Amoco’s Chief Executive Officer, John Browne agrees that the science of climate change “is provisional and perhaps always will be.” But he says, it “would be unwise and potentially dangerous to ignore the mounting concern over climate change.” Other companies also recognize the scientific uncertainties, but like Browne, believe that sometimes it is important to “make plans and decisions in the face of uncertainty.” The Pew Center on Global Climate Change is a group of 32 major companies supporting the Kyoto Protocol, including Boeing, Lockheed Martin, BP Amoco, Maytag, Whirlpool, DuPont, Toyota, 3M, and United Technologies. Other corporations working to combat greenhouse gas emissions are the oil company Royal Dutch/Shell, aluminum makers Canadian Alcan and French Pechiney, oil sands producer Suncor Energy of Canada, and some power companies such as Canada’s Ontario Power Generation. Moreover, many recognize that Kyoto reductions are only a first step, and promote ideas as to ways to further reduce emissions. They believe they can reduce greenhouse gas emissions and still sustain economic growth.

In 2000, a poll of 425 executives in Fortune 5000 companies (the largest 5000 companies in the United States) found that a majority *favored* regulations to lower industrial carbon dioxide emissions; 71% of the executives thought the government should establish emission limits facility by facility, just as happens in the United States for hazardous air pollutants. More than 40% wanted increased federal taxes on oil and gas, the aim of which would be to reduce demand and encourage energy efficiency. Moreover, 77% favored raising fuel-efficiency standards for cars and trucks. Such reactions indicate that industry does not present monolithic opposition to reducing greenhouse gas emissions.

Are there good business reasons for companies to support reductions in greenhouse gas emissions? Some companies have financial stakes such as making energy-efficient products and environmental controls. Some US companies fear the economy will be harmed if the United States is *not* part of the Kyoto Protocol because European companies will get a head start in developing "climate-friendly technologies." ■ Worldwide, 68 insurance companies are fighting to combat global warming. These companies insure against climatic events such as severe storms. They fear the increased incidence of extreme events that warming brings, which could lead to the loss of great sums of money; some could go out of business. ■ Executives in some businesses believe too that emission controls will sooner or later be mandated, and want to get a head start. ■ Most also recognize that many energy-conservation projects – which reduce carbon dioxide emissions – mean spending less on energy.

A number of corporations, working with the environmental organization Environmental Defense, pledged to reduce greenhouse gas emissions at all their facilities worldwide. Some of these companies will also provide technical advice to other businesses. Those that voluntarily reduce greenhouse gas emissions provide examples for others. This is especially important in the United States, where the government rejected the Kyoto Protocol. But most observers believe that voluntary cooperation is not enough. After the Kyoto Protocol comes into force, businesses in those countries that have ratified it will need to adhere to specific reductions. Once that happens, there will be more pressure on US corporations to follow suit.[4]

Box 7.4 | Corporate cuts in greenhouse gas emissions

Many energy-conservation and efficiency steps are appropriate to all companies, but some approaches are more specific.

- BP Amoco will continue energy-efficiency measures within its facilities to reduce carbon dioxide emissions. It will participate in joint implementation projects with other nations to reduce or offset part of BP's greenhouse gas emissions, and establish a pilot emissions-trading program. BP also plans increases in solar technology investment and hopes to expand its photovoltaic energy business ten-fold by 2010.
- Certain DuPont facilities release greenhouse gases other than carbon dioxide, e.g., nitrous oxide and fluorochemicals. Both these gases absorb infrared radiation much more strongly than does carbon dioxide (Table 7.1). DuPont plans, by 2010, to reduce emissions of these by 65% compared to 1990. Also, DuPont pledges

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[4] The Kyoto Protocol will come into effect once it has been ratified by 55 nations producing more than 55% of the developed world's greenhouse gases.

not to increase its energy use as compared to 1990, but will increase its use of renewable energy sources to provide 10% of energy needs by 2010.

- Motorola uses the strong infrared absorbers, perfluorocarbons (PFCs) to etch and clean semiconductors. It aims to halve its use of PFC by 2010 by finding other means to clean its semiconductors. More generally, the World Semiconductor Council decided to urge a 10% reduction in PFC emissions, compared with 1995 levels, at all member facilities worldwide by 2010.
- Sulfur hexafluoride is a particularly potent greenhouse gas with 24 000 times the warming potential of carbon dioxide. It is used to produce magnesium and magnesium parts. As societal use of magnesium increases so will sulfur hexafluoride use unless steps are taken. Recognizing this, 12 magnesium-producing companies formed a partnership to find means of reducing emissions of this gas.

State and province reductions

Some states and provinces are also voluntarily taking action. In 1998, the US state of New Jersey set a goal to reduce its greenhouse gas emissions to 3.5% below 1990 levels by 2005. One reason for taking action was the concern that, as a coastal state, it is vulnerable to rising sea levels. To lower greenhouse gas emissions, it is necessary to determine current emissions. New Jersey's inventory showed that 88% of its greenhouse gases came from burning fossil fuel. Of this, transportation contributed 38%, energy use in residential buildings 24%, energy use in commercial buildings 22%, and industrial energy use 16%. New Jersey's second step was to establish specific goals to reach by the year 2005 to reduce emissions from each sector.

- Industry. One way that this sector will reduce energy use is that, whenever they need to replace a motor, it will replace all fixed-speed motors with variable-speed motors. (Industrial motors are a major use of electricity. Variable-speed motors are superior because they are run to use only the amount of energy a task requires whereas a fixed-speed motor runs at high speed at all times.) Industry can also reduce energy loss by actions such as repairing steam leaks and air compressors.
- Transportation. New Jersey's government will work to reduce emissions from vehicles that it owns. It has begun to purchase energy-efficient vehicles for its state fleet.
- Individuals. New Jersey did not challenge its citizens to reduce emissions. It could have done so by encouraging them to buy more fuel-efficient motor vehicles, or more energy-efficient household appliances.

Other US states have begun to follow New Jersey's example. ■ In 2002, California passed a law requiring limits on emissions of CO_2 by cars and trucks. Massachusetts and New Hampshire enacted bills to cut power plant emissions of CO_2. New York plans "aggressive" steps to reduce its greenhouse gas emissions. Other states likewise have developed Climate Action Plans. ■ In 2002, an organization composed of the Governors and Premiers of US New England states and eastern Canadian provinces strongly committed to cut greenhouse gas emissions.

City reductions

Over 400 cities around the world, such as Toronto and Boston, are part of an organization, Cities for Climate Protection. Each city calculates its greenhouse gas inventory, sets a target for reducing emissions, and develops a plan to meet its target. Boston, Massachusetts committed itself to reducing municipal energy use 10% by 2005. Boston is doing this by working on practices such as reducing energy use by streetlights, buildings, and transportation. Cities act not only to reduce greenhouse gas emissions, but to save money through increased energy efficiency. They also reduce local air pollution, and develop new jobs creating, installing, and maintaining new technologies. ■ College and university campuses, organizations, and individuals are also becoming active in the move to reduce greenhouse gas emissions. Any one reduction may be tiny. Added together they are significant and are also significant in the role of setting examples to others.

Adaptation and remediation

Carrying out the emissions reductions specified in the Kyoto Protocol is important, but it is only a first step. It will not halt the warming. We must also consider measures to adapt to or mitigate the effects of climate change. ■ An example of *mitigation* is to erect a sea-wall to prevent coastal flooding as sea levels rise, or to stop salt water intrusion into groundwater and into drinking water systems. Another proposed mitigation measure, still at the research stage, would be developing crops and animals better adapted to warmer climates, or to dry or saline soils. ■ *Sequestration* of CO_2 is a mitigation possibility being widely explored. CO_2 emissions are captured from a source such as coal-burning power plants and sequestered, i.e., stored in a way that they cannot reach the atmosphere again in the foreseeable future. One way to sequester CO_2 is to inject it deep into the ocean, which as you recall is already a huge CO_2 reservoir; or, inject it into deep aquifers under sea or land. Sequestration generates enormous controversy: how long before CO_2 deposits escape from their storage locations, or how does concentrated CO_2 harm ocean ecosystems at the point of injection? Research aimed at answering such questions includes studying ocean mixing and the circulation of ocean currents.[5] ■ Even more controversial is the idea of fertilizing oceans with iron – to stimulate the growth of ocean plankton; as more

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[5] Another major concern generated controversy: At some future time, might large quantities of CO_2 be released precipitously? This would be undesirable, and not just because the CO_2 would return to the atmosphere, but because at high doses CO_2 too can be toxic. Precipitous release could in some circumstances expose living creatures to CO_2 concentrations large enough to asphyxiate them by blocking inhalation of enough oxygen. This is not a theoretical concern. In 1986 the volcanic crater lake, Lake Nyos in Cameroon released a huge CO_2 'bubble', which killed about 1500 people and all animal life up to 14 km from the point of release.

plankton grow, they take up more atmospheric CO_2. ■ An idea more acceptable to many is developing long-lasting products that chemically lock CO_2 into them. These would be analogous to the CO_2 now locked into wood in houses or into the paper of this book. However, instead of wood or paper, these would be synthetic products that are produced using captured CO_2. Some minor uses already exist for captured CO_2.[6]

Box 7.5 | Carbon sequestration is already being used

Trapping CO_2 emissions to prevent them from entering the atmosphere is expensive. However, Norway has had a *carbon tax* since 1991, about \$55 per ton (\$50 per tonne) of CO_2 emitted. This tax stimulated oil and gas companies to consider how to minimize CO_2 emissions. Statoil, Norway's state-owned oil company recovers natural gas, which is contaminated with 9.5% CO_2. They must reduce this to 2.5%, the limit for commercial natural gas. Because Statoil had to trap CO_2 anyway, it cost the company relatively little to do the following. Since 1998, it has pumped about a million tons of CO_2, about 3% of Norway's CO_2 emissions, into an immense offshore aquifer 800 m below the floor of the North Sea. This operation adds about 1% to the cost of natural gas production, small compared with the carbon tax. The storage aquifer is a porous sandstone formation filled with salt water. Norway's Petroleum Research group believes such disposal is permanent and safe. It calculates that enough capacity exists in North Sea aquifers to sequester CO_2 emissions from all EU power plants for hundreds of years. Modeled results indicate that it would take over 10 000 years before even small amounts of the CO_2 would escape up to the floor of the ocean.

Questions 7.2

1. What is your initial reaction to learning of projects that sequester CO_2? Explain.
2. What is your reaction to the Statoil project?
3. What more might you like to know about sequestration to enhance your confidence that it could safely be used to store CO_2?

Action in less-developed countries

It was difficult for those negotiating the Kyoto Protocol to reach agreement on reducing emissions to even 5% below 1990 emissions; 5% is small, but starts the process. Even 5% will be a struggle because the world's use of fossil fuels is rapidly increasing. In 2000, the US Department of Energy projected that world energy use would rise 60% by 2020, compared with 1997 levels, and more than that in

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[6] Uses for CO_2 include pumping it into oil wells, where it enhances oil recovery. Small amounts are used in the pulp and paper industry to make calcium carbonate, a paper coating and filler. Some goes into sodium carbonate, an industrial chemical which is also used in washing soda. And some is used in carbonated beverages. However, none of these applications make a dent in the major amounts of CO_2 released.

developing countries. Carbon emissions will increase because more energy is needed, and much of the additional energy will come from coal burning. One reason that the United States refused to ratify the Kyoto Protocol is that less-developed countries, even those ratifying the treaty do not have quantified targets for greenhouse gas reductions. However, consider the point of view of those from poor nations: the average American emits perhaps 20 times more CO_2 than the average Indian. This observation has led many to conclude that developed countries such as the United States must lead the way – find means to lower their own greenhouse gas emissions, develop new technologies while doing so, and transfer those technologies to poor nations.

China

Only industrialized nations are formal parties to the Kyoto Protocol, but some developing nations find it in their interest to ratify the treaty. Doing so makes them eligible to receive assistance from developed nations making use of the flexibility mechanisms noted above. For instance, some coal-burning utility companies have reforestation and energy-efficiency projects in poorer nations. The contributing companies find that they accomplish reductions more cheaply than by making major modifications to their own facilities. And, they receive credit for emissions reduction. The less-developed country for its part has a new technology and the added employment that a new investment generates. Both sides gain. China's Xinhua News Agency reports that China wants to work with other nations on climate change. Its coal-burning power plants produce 80% of electricity now, and expectations are that China will be the globe's largest CO_2 source by 2020. However, China is changing too. A year 2001 *Science* article[7] reported that Chinese CO_2 emissions fell 7% compared with emissions in the peak year 1996. One reason that CO_2 emissions slowed was the Asian economic crisis of the late 1990s, which led to slowed production in, or shutting down of, many factories. But there is actual action too: China is reducing subsidies to its coal industry, and has shut down some of its worst-polluting industries. Energy efficiency is improving too. China's reliance on coal burning is falling, and many coal mines have been shut down. Economic growth has not slowed. ■ Because China has suffered soil erosion and flooding from widespread deforestation, and trees help to protect the water supply, this nation is also planting huge numbers of trees to take up CO_2. ■ China's methane emissions also are reportedly 2% lower than in their peak year of 1997. ■ And although per capita, US CO_2 emissions were already nine times higher than in China, US emissions are growing faster. China's people, its environment and crops suffer greatly from pollution associated with fossil-fuel burning. So, aside from reducing greenhouse

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[7] Streets, D. G., Jiang, K., Hu, X., Sinton, J. E., Zhang, X., Xu, D., Jacobson, M. Z., and Hansen, J. E. Climate change: recent reductions in China's greenhouse gas emissions. *Science*, **294**(5548), 30 November, 2001, 1835–37.

gas emissions, when China takes steps to lower CO_2 emissions it also lowers emissions of other damaging pollutants.

India and other less-developed nations

China has one-fifth of the world population, but India too has a population of over a billion and is still growing. India too greatly depends on coal. Along with other Asian nations, and African and Latin American nations, India needs assistance from the industrialized world. ■ Low-lying island countries have the problem of surviving at all as sea levels continue to rise.

Studies led by the University of California, Davis indicate that the developing world's rapidly growing megacities, such as Delhi, India do have low-cost options to lower emissions of CO_2 and soot. These include improved sidewalk and bicycle networks, and better public transportation. Countries can promote clean efficient motorcycles, scooters, smaller cars, and cleaner engine technologies. Recall that incomplete combustion is responsible for soot emissions, and efficient engines produce less. Because some warming is considered inevitable, the UN Environmental Program is also working on means to help poor countries in their mitigation efforts. In particular, how can countries ensure dependable food production as the climate warms? For instance, Mongolia greatly depends on its grasslands to graze animals. How can the grasslands survive climate change? Or, how could better weather forecasts help Nigeria and Niger improve cereal production? Eileen Claussen, president of the Pew Center on Global Climate Change has said that, "One of the greatest challenges we face in addressing climate change is helping developing countries forge cleaner, more sustainable paths to development."

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Chapter 8

Stratospheric-ozone depletion

"If all the ozone in the atmosphere were compressed to a pressure corresponding to that at the earth's surface, the layer would be only 3 mm [0.118 in] thick. . . The thin stratospheric-ozone layer has proved to be an Achilles' heel that may be seriously injured by apparently moderate changes in the composition of the atmosphere."

Swedish Academy of Sciences, announcing the award of the 1995 Nobel Prize for Chemistry to Mario Molina, F. Sherwood Rowland, and Paul Crutzen

You have read in this text many times of the major pollution problems resulting from combustion, especially fossil-fuel combustion. In this chapter we see a global issue – destruction of stratospheric ozone – which does not result from combustion. The chemicals responsible are synthetic chemicals, *chlorofluorocarbons* (CFCs) and *halons*. Stratospheric ozone is essential to life on Earth. It absorbs more than 95% of the sun's ultraviolet (UV) radiation, which could otherwise destroy most life. Stratospheric-ozone depletion led to the 1987 Montreal Protocol, the first worldwide agreement to protect the environment. Except for smuggled chemicals, the ban of ozone-depleting chemicals is working. The stratospheric-ozone layer is expected to recover, albeit slowly. **Section I** below examines the stratosphere and provides background on CFC uses and how ozone depletion was detected. In **Section II**, we see why the greatest ozone depletion occurs over Antarctica, and describe the increases in UV radiation reaching the Earth. **Section III** brings us to the pollutants that deplete ozone and their sources, and a description of concerns associated with increased levels of UV radiation reaching the Earth. The reduction in atmospheric levels of ozone-depleting substances as a result of the Montreal Protocol is introduced in **Section IV**, as is the smuggling of CFCs and halons that could threaten the effectiveness of this treaty. Finally, **Section V** describes what the future holds in terms of alternatives to

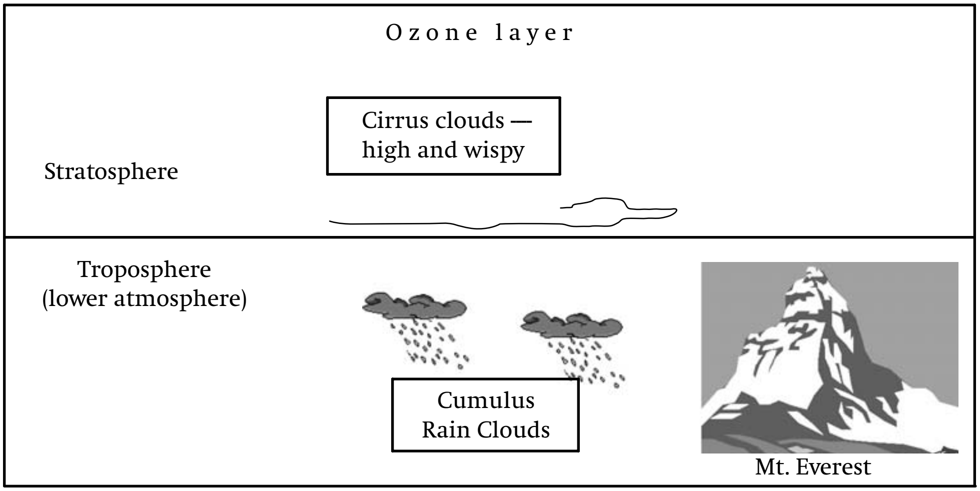


Figure 8.1 The atmosphere up to about 50 km (not to scale). Mount Everest is about 8.9 km high. Source: US National Oceanic and Atmospheric Agency

ozone-depleting chemicals and for the restoration of the stratospheric-ozone layer.

SECTION I

The stratosphere and ozone

The lower 10 km of our atmosphere is called the "troposphere." It is the atmospheric layer within which we live. The troposphere contains about 90% of all air molecules. The stratosphere lies just above the troposphere, 10 to 50 km above Earth (Figure 8.1). Although it contains but 10% of the atmosphere's air molecules, it has 90% of its ozone. Only 10% of ozone is in the troposphere. Stratospheric ozone absorbs more than 95% of the sun's UV radiation, which would otherwise reach and damage human, animal, plant, and microbial life. In the stratosphere there is an ongoing natural cycle in which ozone is formed, destroyed, and reformed (Box 8.1).

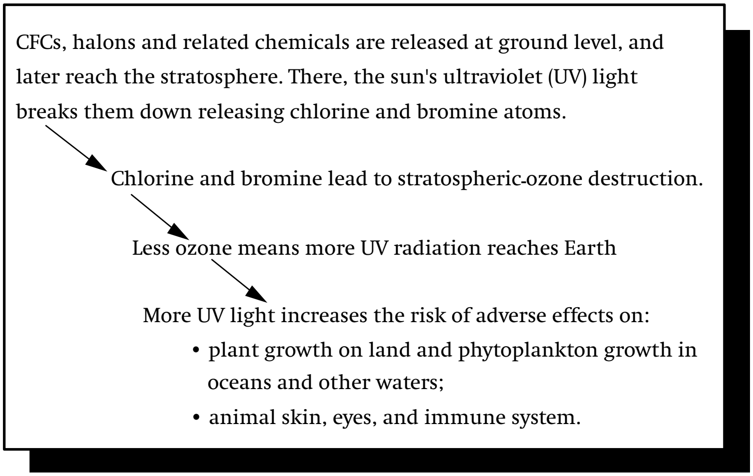
Box 8.1 | A bit of chemistry – making and remaking ozone (O_3)

Reaction 1. The energy of the sun's ultraviolet (UV) radiation breaks diatomic oxygen (O_2) into single oxygen atoms (O).

- O_2 + UV radiation → O + O (oxygen atoms)

Reaction 2. An oxygen atom reacts with O_2 to form ozone (O_3).

- $O + O_2 \rightarrow O_3$



CFCs, halons and related chemicals are released at ground level, and later reach the stratosphere. There, the sun's ultraviolet (UV) light breaks them down releasing chlorine and bromine atoms.

Chlorine and bromine lead to stratospheric-ozone destruction.

Less ozone means more UV radiation reaches Earth

More UV light increases the risk of adverse effects on:

- plant growth on land and phytoplankton growth in oceans and other waters;
- animal skin, eyes, and immune system.

Figure 8.2 An ozone-depletion snapshot

Reaction 3. UV radiation dissociates an O_3 molecule into O_2 and one oxygen atom.

- $O_3 + \text{UV radiation} \rightarrow O + O_2$

Reaction 4. Remaking ozone.

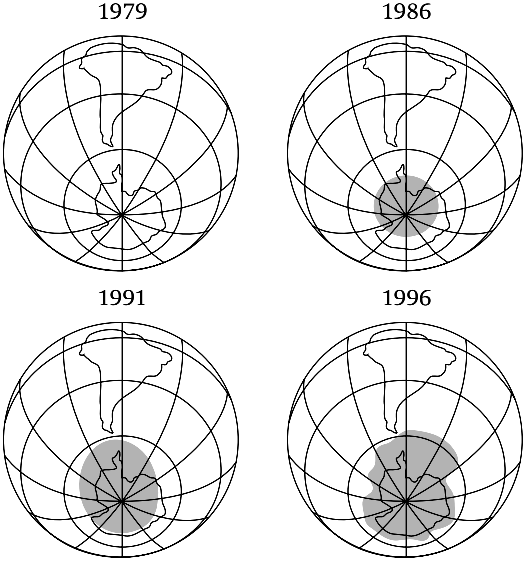
- $O + O_2 \rightarrow O_3$

A brief history of ozone depletion

A hundred years ago, the new refrigeration industry used highly toxic gases, such as ammonia and sulfur dioxide, as coolants. Accidental leakage of such chemicals resulted in many human deaths, and in the 1920s, the US Congress attacked manufacturers for producing “killer refrigerators.” Then, in 1928, a young chemist announced the creation of a new coolant. Later he demonstrated that he could directly inhale the coolant – it had low toxicity. When exhaled, the breath could be used to blow out a candle – so it was not flammable. This impressive coolant was a chlorofluorocarbon (CFC). In 1931 it was introduced into the market as *Freon*. Its safety made it seem a godsend and Freon became widely used in refrigerators and, later, air conditioners. Other CFCs found other applications: aerosol-can propellants, industrial solvents, cleaning agents, and insulating agents (in which CFCs are blown into foam products or polystyrene cups). ■ *Halons* are related to CFCs, but contain the element, bromine rather than chlorine. Halons became important fire-fighting chemicals.

Another property of CFCs and halons that made them so useful industrially was their lack of chemical reactivity. This stability was their Achilles’ heel. By the 1970s scientists found they were spreading around the globe. With nothing to break them down it was estimated that CFCs would survive hundreds of years. Their curiosity piqued by

Figure 8.3 Growth of the Antarctic ozone hole. The shaded area shows the zone of ozone depletion. Source: US National Oceanic and Atmospheric Administration



such information, Professors Mario Molina and F. Sherwood Rowland made calculations that led to a hypothesis that CFCs would lead to significant depletion of the stratospheric-ozone layer. Molina subsequently examined the question: Why does the greatest ozone depletion occur over Antarctica?[1] (See Rowland and Molina, 1994 in Further reading.)

Laboratory work demonstrated that high-frequency UV light could break down CFCs. One of the chemicals into which CFCs were degraded was elemental chlorine; this could catalyze the breakdown of ozone (O_3). In nature, the high-intensity UV light necessary to degrade CFCs and halons is found only in the stratosphere, and CFCs were found to be making their way into the stratosphere. By 1976, scientists believed that CFCs were threatening stratospheric ozone. At that time, two-thirds of manufactured CFCs were used as aerosol propellants, and in 1979, the use of CFCs as propellants was banned by the United States and, later, by a number of other governments. Thereafter, concern about stratospheric ozone lessened. The quietude ended in the 1980s when a group of British researchers, making ground-based measurements of the ozone above Antarctica, reported a 30% decline compared with its levels in earlier years. These researchers had actually observed October (spring) depletion as early as 1977, but doubted their own observations. When they reported their findings in October 1985, the US National Aeronautics and Space Administration (NASA) confirmed their observations using satellite and airborne

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[1] In 1995, Professors Mario Molina and F. Sherwood Rowland won the Nobel Prize for Chemistry. This was the first time that a Nobel Prize recognized research into man-made impacts on the environment. They shared the prize with Professor Paul Crutzen, who showed that nitrogen oxides accelerated ozone depletion. This finding led to cancellation in the 1970s of a planned fleet of supersonic aircraft, which would have released nitrogen oxides directly into the stratosphere.

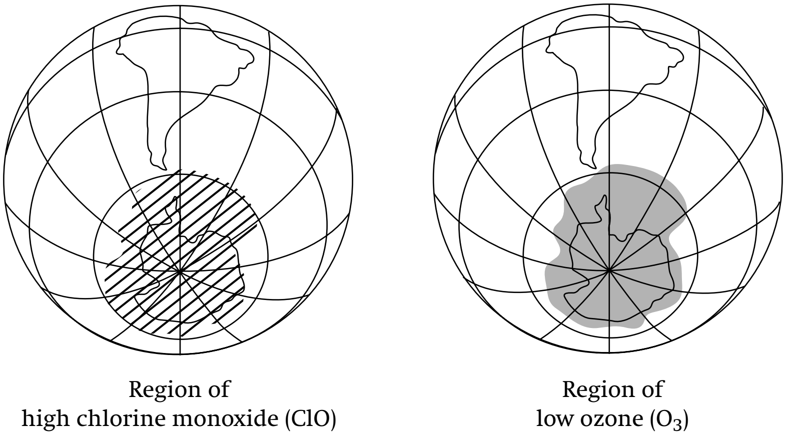

Figure 8.4 Chlorine monoxide and the Antarctic ozone hole: late August 1996. Source: US National Oceanic and Atmospheric Administration

measurements of stratospheric ozone. Since then, Antarctica's spring "ozone hole" has been actively monitored. A US National Oceanic and Atmospheric Administration (NOAA) representation of ozone disappearance over Antarctica after 1979 is seen in Figure 8.3. The region outlined at the bottom of the globe is Antarctica. By 1986, a disappearance of ozone (shaded area) is seen over this continent. This area became increasingly obvious in 1991 and 1996.[2]

SECTION II

Antarctica

Up to 60% of the ozone disappears over some parts of Antarctica during its September–November spring. Antarctica is much more vulnerable to ozone depletion than other locales. This sensitivity results from the ice-particle clouds, polar stratospheric clouds (PSCs) that form during the tremendously cold winters. PSCs are trapped within a *polar vortex*, formed by strong wind currents circulating around the pole. The vortex prevents air from mixing with the atmosphere beyond the Antarctic. ■ Crucially, the PSC ice particles provide surfaces on which CFCs can decompose into the highly reactive chemicals chlorine and chlorine monoxide (ClO). ■ Then, the UV radiation of the returning spring sun assists chlorine monoxide in reacting with and destroying ozone. Later in the spring, as the atmosphere warms, the ice particles and the vortex dissipate. The polar air can then mix with the atmosphere beyond Antarctica, and stratospheric-ozone levels return to normal. ■ In Figure 8.4, notice that the region where chlorine

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[2] Ozone is measured in Dobson units (DU). The normal stratospheric-ozone layer thickness is about 300 DU. Antarctic ozone records date back to the 1920s when Dobson developed the Dobson spectrophotometer and began making measurements from the ground. Remote sensing of ozone from satellites began in 1960. Currently, ground-based and satellite-based instruments monitor stratospheric-ozone levels not only over the Antarctic, but over the Arctic and 80 other sites worldwide.

monoxide is found in higher amounts corresponds to the "region of low ozone" where ozone destruction occurs. In addition to using satellites to follow the chemicals in the stratosphere under various conditions and times, the chemical reactions leading to ozone destruction have been well studied under laboratory conditions set up to simulate atmospheric conditions.

Ozone thinning beyond the Antarctic

Ozone thinning is seen, but to lesser extents, in places other than Antarctica.

- Some thinning, typically about 15%, is seen over the Arctic. In one exceptionally cold winter, ozone depletion reached 30%. These losses are smaller than in Antarctica for several reasons. One is that the less-cold Arctic forms fewer stratospheric ice particles.
- Ozone losses measured by ground-based and satellite instruments, are seen over middle-latitude countries, the United States, Canada, and Europe too. The losses observed are lower than in the Arctic, about 2.7% a decade. By 1996, ozone was 5% to 8% lower than 1957 to 1970 levels. Similar losses are seen in middle-latitude countries of the southern hemisphere.

Volcanic eruptions

But how can we explain ozone losses in places where there are no stratospheric ice particles to provide surfaces that allow the destructive process? Here is where a chemical with which you are familiar, sulfur dioxide, enters the picture. Volcanic eruptions release huge quantities of sulfur dioxide. This reaches the stratosphere as sulfuric acid. The sulfuric acid aerosol serves the function of ice particles, providing a surface for reactions leading to chlorine-catalyzed ozone depletion. Volcanic eruptions appear to exert major effects in the year-to-year fluctuation seen in stratospheric-ozone depletion. ■ In 1993, a NASA satellite recorded stratospheric-ozone levels over Antarctica of 88 Dobson units (DU) compared with a normal level of 300 DU (see footnote 2). This was the greatest Antarctic thinning, or ozone hole, observed up to that time, and was ascribed to particles formed after the eruption of Mt. Pinatubo in the Philippines in 1991. Because sulfate particles settle out of the stratosphere, investigators hypothesized they should be gone by 1994. Indeed, Antarctic ozone levels partially recovered in 1994 reverting to the slower – but still ongoing – depletion rate seen before the volcano erupted.

Other sulfur dioxide sources

Even when there is little volcanic activity, two other sources of sulfur dioxide to the stratosphere exist. One is *carbonyl sulfide* naturally produced in the ocean and continually transported into the stratosphere, where it is converted into sulfur dioxide. The other source of sulfur dioxide comes from the troposphere – from human pollution. This appears to be able to move into the stratosphere. But particles alone don't deplete ozone: it is the interaction of ozone-depleting chemicals with the particles – whether ice particles or an aerosol formed from sulfur dioxide – that causes the problem.

Ultraviolet radiation

Ultraviolet radiation

UV radiation is divided into UV-A, UV-B, and UV-C. The wavelength of UV-C is the shortest of the three, and has the highest energy. UV-B is of intermediate energy, and it is UV-B that is usually referred to in discussions of UV radiation and its harm to life. *Larger amounts of harmful UV radiation can reach Earth if there is less ozone in the stratosphere.* Can this statement be confirmed? Measurements of UV are straightforward and were first made in the late 1800s. However, detecting small increases in UV radiation beneath an area of ozone depletion can be difficult, especially if the amount of depletion is small. This is due to several factors. ■ Clouds absorb part of the UV radiation with thicker clouds absorbing more; clouds also scatter some radiation. ■ The UV radiation reaching Earth varies with the time of day and the season of the year. ■ It varies in a more regular way with latitude: the closer to the equator one moves, the greater the amount of UV radiation reaching Earth. Radiation at the equator is about a thousand times greater than at the poles. ■ More radiation reaches Earth at higher elevations as compared with ground level. ■ And remember ground-level ozone. As with stratospheric ozone, ground-level ozone absorbs UV radiation too. In ozone-polluted areas more UV is absorbed. ■ Other air pollutants also absorb some UV radiation. If you think of all these variables, you can see why it is difficult to demonstrate a greater amount of UV radiation reaching the Earth due to stratospheric-ozone thinning.

You might expect that it would be easier to clearly see increases in UV radiation reaching Antarctica during its spring when a great deal of ozone depletion is occurring overhead. And indeed, the most clearly demonstrated increases in UV radiation are seen in Antarctica beneath regions of depleted ozone. In fact, the UV radiation reaching Antarctica in its spring can be even greater than that reaching the ground in San Diego, California; San Diego would naturally receive more UV because the sun is much higher above the horizon. ■ Clear increases in UV can also be measured at the Arctic pole during its spring in March. ■ It is more difficult to detect UV increases under regions where only a small amount of ozone has been depleted. Still, this has been accomplished in numerous places from Texas, to Canada and Switzerland. ■ To evaluate UV radiation reaching the Earth more accurately, measurements are taken on clear days, and in areas far from major cities and their air pollution. More broadly, satellite measurements now follow global changes in UV radiation, and make corrections for cloud cover.

SECTION III

Ozone-depleting pollutants

Ozone-depleting pollutants and their sources

The source of ozone-depleting chemicals in the stratosphere is the manufacture of chlorine-containing and bromine-containing chemicals by humans, especially CFCs and halons.[3] ■ CFCs are no longer manufactured in industrialized countries, but remain in older refrigeration equipment including automobile air conditioners. Freon-12 (CCl_2F_2) was the most widely used refrigerant. ■ Another less-potent group of ozone-depleting chemicals is the *halocarbons*. These synthetic chemicals contain carbon plus at least one halogen (fluorine, chlorine, bromine, or iodine). Ozone-depleting halocarbons include the fumigant *methyl bromide*, the specialized refrigerant *methyl chloride*, and the solvents *methyl chloroform, carbon tetrachloride, and 1,1,1-trichloroethane*. About 20% of the chlorine reaching the stratosphere is natural and the other 80% is that in synthetic chemicals. ■ The fire-fighting chemicals, halons, were the largest source of ozone-depleting bromine. Now the largest source of bromine is the fumigant *methyl bromide*. Marine organisms and forest and grass fires also generate significant amounts of methyl bromide. ■ A 1995 report indicated that iodocarbons (iodine-containing chemicals) may also deplete ozone.

Each CFC and other ozone-depleting chemicals are rated according to an ozone depletion potential (ODP). CFC-12 (Freon) was given a value of 1. Halon 1301 has an ODP of 10; that is, it is 10 times more destructive than CFC-12. On the other hand, methyl chloride has an ODP of about 0.1; that is, it is 10 times *less* destructive than CFC-12. Nature produces the lion's share of methyl chloride, about 5 million tons (4.5 million tonnes) as compared with only 26 000 tons (23 600 tonnes) from human activities. Iodine, an element in the same family as chlorine and bromine, may be important in ozone depletion too, but in this case nature produces iodocarbons in amounts that dwarf human contributions. The amount of iodocarbons that reach the stratosphere is unknown.

Not all chlorine and bromine chemicals deplete ozone

Water-soluble chemicals are much less likely to deplete ozone. A major instance is hydrochloric acid (HCl), produced in huge quantities by volcanic eruptions. However, HCl is water soluble and almost all is washed out before reaching the stratosphere. Sodium chloride in ocean spray does not reach the stratosphere for the same reason. Other water-soluble forms of chlorine include those used for water disinfection, swimming pools, or bleach. It is the water-*in*soluble CFCs and halons that are not rained out of the atmosphere. They survive to reach the stratosphere, where they cause mischief.

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[3] Volcano vents are a natural source of CFCs, but release them in tiny amounts as compared with the quantities produced by humans.

Why ozone-depleting chemicals concern us

Some chemical and physical factors

In earlier chapters you became familiar with a number of organic pollutants including polychlorinated biphenyls (PCBs) and polychlorinated pesticides that are persistent in the environment. However, CFCs and halons are much more stable, so much so that they may persist in the atmosphere for up to 200 years. They are heavier than the air molecules oxygen and nitrogen. In fact, skeptics previously argued that CFCs could not reach the stratosphere because of their heaviness. However, because CFCs and halons are not rained out and are so stable, they survive to mix with air masses moving into the stratosphere. Indeed, they are measured in the stratosphere by instrumentation aboard balloons, aircraft, and satellites. ■ In the stratosphere, CFCs and halons finally encounter an agent – UV light from the sun – that can destroy them. When CFCs do react, the major product of their degradation is free chlorine (or free bromine atoms from halons). It is the highly reactive chlorine that, after conversion to chlorine monoxide, reacts with ozone to destroy it. *If each atom of chlorine or bromine destroyed only one atom of ozone, there would be no problem.* But they act as catalysts – one chlorine atom can destroy many thousands of ozone molecules, and one bromine atom is much more destructive still. Thus chlorine and bromine destroy ozone disproportionately to their low concentration (Box 8.2)

Box 8.2 A bit of chemistry – destroying ozone with CFCs

CFC-12 (Freon) is the best-known CFC. Its formula is CF_2Cl_2. Below (simplified) are reactions that result in ozone destruction.

Reaction 1.

- CF_2Cl_2 + UV radiation $\rightarrow$ CF_2Cl + Cl (single chlorine atom)

Reaction 2a.

- $Cl + O_3 \rightarrow O_2 + ClO$ (chlorine monoxide)

Reaction 2b.

- $ClO + O \rightarrow Cl + O_2$

Net reaction of 2a and 2b is:

Reaction 2c.

- $O_3 + O \rightarrow 2O_2$

i.e. the ozone has been destroyed.

One ClO molecule can catalyze the destruction of many thousands of ozone molecules. Chlorine is eventually converted to a water-soluble chemical such as hydrogen chloride (HCl), which can then be deposited from the stratosphere.

The harm to life of ultraviolet radiation

UV radiation can harm any living creature exposed to it. This includes phytoplankton (microscopic algae) at the bottom of the food chain on which all animals, including humans, depend for food, directly or indirectly. The productivity of these critical tiny organisms is one reason why a threat to stratospheric ozone raises serious concerns. A 1985 report projected that, if CFC use continued at the 1985 rate, a 7% loss of stratospheric ozone would occur by the year 2050. This seems a relatively small loss, but it could increase the Earth's UV radiation enough to harm the vital phytoplankton. A 1994 UN Environmental Program study reported that increased UV-B radiation was reaching the water's surface in the Antarctic, and causing phytoplankton losses plus developmental damage to fish, shrimp, crabs, amphibians, and other animals. However, because of very large uncertainties in the data, quantitative estimates of adverse effects were impossible.

Natural levels of ultraviolet radiation

For a moment, forget about stratospheric-ozone depletion. Consider overexposure to "normal" sunlight, especially summer sunlight, and especially if you are moving toward the equator, or up a mountain. Overexposure to even "everyday" levels of sunlight can seriously affect your health. Midday summer sun is the worst, but other parts of the day can also lead to overexposure. ■ In eyes, overexposure can lead to cataracts. ■ In skin, adverse effects of overexposure include sunburn, premature skin aging, and skin cancer. Cancer occurs because UV light damages the genetic material, DNA, within skin cells. Cells can repair DNA, but not all breaks are repaired. There is no such thing as a healthy tan.

Natural levels of UV light can be deleterious. Thus, any increase in UV radiation resulting from stratospheric-ozone depletion must be taken seriously. For each 1% increase in UV-B radiation reaching the Earth, there is a projected 2% increase in non-melanoma skin cancers. These are cancers associated with cumulative exposure to sunlight over the years. The more serious skin cancer, malignant melanoma, is associated not with cumulative exposure, but with periods of intense exposure or sunburn that occurred early in life. Skin-cancer incidence has increased rapidly in recent decades, but started its sharp increase years before stratospheric-ozone declined. Thus, changes in lifestyle were the suspected cause. People spend more time in the sun, often around midday, when UV radiation is most intense. Often, clothing is inadequate for skin protection, and perhaps 40% of people wear inadequate sunscreen protection. Diet may also contribute to the development of skin cancer. But – even though lifestyle is *currently* the major factor in the increased incidence of skin cancer – researchers believe that increasing radiation resulting from ozone depletion will further increase cancers. In 2001, Chilean scientists published a report that they believe shows a direct link between ozone depletion and skin problems. A medical doctor working with climatologists found sun blisters appearing on people's skin on the same days that ozone depletion over the Antarctic expanded to cover southern Chile.

■ Because the skin contains immune cells, UV radiation can suppress the immune system. This may be observed as an increase in cold sores during the first sunny days of summer; these cold sores result from activation of latent (dormant) herpes virus. More generally, an increase in infectious illnesses is seen in those with suppressed immune systems; that is, in people whose immune systems are already weakened by other illnesses or age. Although immune-system suppression occurs more readily in fair-skinned people, dark-skinned people are also susceptible. Again, increasing radiation resulting from ozone depletion could increase these problems. ■ UV radiation also subjects materials, such as plastics and other organic materials, to photodegradation. ■ And remember that ground-level ozone is formed in the largest amounts in summer under the sun's strongest UV radiation. So, increased UV radiation could increase ground-level ozone ("bad ozone") levels although paradoxically, ground-level ozone also absorbs UV radiation. Stratospheric ozone, critical for the protection of life on Earth, is the "good ozone."

CFCs and climate

■ CFCs are potent greenhouse gases, many thousands of times more potent than carbon dioxide (see Internet resources, Current Greenhouse Gas Concentrations). They absorb certain wavelengths of infrared radiation emanating from Earth; wavelengths that are not absorbed by other gases. ■ On the other hand, CFCs *cool* the stratosphere. This happens because ozone normally absorbs the sun's energy as it breaks down. This warms the stratosphere. With ozone destroyed, there is less to interact with the sun's radiation. So, the stratosphere cools. This may balance out the warming caused by CFC action as a greenhouse gas. ■ There may be interactions between ozone depletion and global climate change, a possibility now being studied.

Contrary views on stratospheric-ozone depletion

Scientists almost all agree that CFCs, halons, and related chemicals can destroy stratospheric ozone. However, as happens with many environmental issues, there are skeptics. And often, as with ozone, researchers respond to skeptics by doing more research. ■ At one time, skeptics asserted that a drop in Antarctic ozone had been reported in the 1950s, at a time before CFCs were widely used. However, a NASA researcher re-analyzed the data on which that 1950s report was based, and found that instrumental errors explained what was thought to be a lowered level of stratospheric ozone. As a 1994 *Science* article stated, "There is no credible evidence for an ozone hole in 1958." ■ Skeptics asserted yes, there is chlorine in the stratosphere, but it is chlorine from volcanic eruptions, not CFCs. NASA researchers subsequently demonstrated that CFCs did reach the stratosphere and were degraded there: satellite instruments detected the refrigerant CFC-12 in the stratosphere. The amount of CFC-12 decreased above 20 km, a level where the sun's high-energy UV radiation breaks it down. At levels where CFC-12 was detected, its breakdown products – hydrogen chloride and hydrogen fluoride – were also detected. Stratospheric levels of hydrogen fluoride have increased steadily over the years. Such a steady build-up is not consistent with the hypothesis that hydrogen fluoride is produced by intermittent volcanic eruptions.[4] Scientists directing the NASA project stated that CFCs are the source of chlorine in the stratosphere, stressing, "There is no other possibility." Other work firmly established the link between chlorine build-up in the stratosphere and ozone loss. An estimated 20% of stratospheric chlorine is from natural sources, as compared with 80% from human activities.

■ Skeptics also go another step and say, yes, CFCs do reach the stratosphere, but they don't destroy a significant amount of ozone. They say, we have only been measuring stratospheric-ozone levels for about 40 years, and don't know enough about natural fluctuations to know that ozone is being perturbed. They point out that stratospheric-ozone levels, even in one location, can naturally vary by 40% over a period of a few weeks. ■ Critics also say too that the amount of UV radiation reaching Earth varies greatly (and naturally) with degrees of latitude. For every 60 miles (97 km) that a northerner travels south, UV exposure increases by 5%; or for every additional 150 ft (46 m) elevation, UV exposure increases by 1%. In Denver – the mile-high city – people have a 35% greater exposure to UV radiation than do Philadelphia citizens; or, one approximately doubles skin-cancer risk by moving south from Chicago to Atlanta because of Atlanta's greater UV radiation. There are answers to these questions. In the case of the equator's heavy UV radiation, we see that life there has evolved means to protect itself from heavy UV doses. Consider the dark skin of tropical peoples, which partially protects them from intense UV radiation. But life at the South Pole evolved with low UV levels and is damaged by higher radiation. In the end, not every point made by skeptics may be fully answered. Policy makers must go with the best-available evidence.

Questions 8.1

1. Students sometimes ask why we can't solve the problem of stratospheric-ozone depletion by pumping ground-level ozone into the stratosphere. Assume that this is practical. Why would this not solve the problem of stratospheric-ozone loss?
2. Why are the large majority of air molecules in the atmosphere found in the troposphere?

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[4] The reason for following hydrogen fluoride (and not hydrogen chloride) is that there is no natural source of this chemical other than volcanoes.

3. Although ozone is heavier than either oxygen or nitrogen, most ozone is found in the stratosphere – why?

4. (a) More UV radiation reaches higher elevations than lower elevations – why?
(b) Why does more UV radiation reach locations that are closer to the equator than those that are further away?

5. In response to stronger UV radiation, plankton can move deeper into the water. This being the case, why are we concerned about the effect of UV on plankton?

6. The banning of CFCs and halons has been difficult. But it is relatively easy compared with what will be required to greatly reduce, let alone ban, carbon dioxide emissions. Why?

SECTION IV

Reducing atmospheric levels of ozone-depleting substances

The Montreal Protocol

Once stratospheric-ozone depletion was observed in the 1980s, many believed that a quick and complete ban was necessary to avert serious consequences, especially because CFCs and halons have atmospheric lifetimes of decades to centuries. In 1987, most industrialized nations signed the Montreal Protocol on Substances That Deplete the Ozone Layer; an agreement to ban CFC and halon manufacture. Many other nations later signed the treaty, which was further strengthened in 1992. The Montreal Protocol was significant because it banned ozone-depleting chemicals, and also because it represented the first global environmental-protection treaty. In the United States, by 1995 almost all CFC and halon manufacture ceased. In small amounts, CFCs continue to be used for purposes deemed essential: as propellants in aerosol sprays used by asthmatics and to manufacture rocket motors. Although no longer manufactured in the United States, CFCs still remain in refrigerators and air conditioners produced before the ban. As these appliances reach the end of their lives, CFCs are collected by trained technicians to prevent their escape into the atmosphere.

Assisting less-developed countries

Production of CFCs in the United States and other Western countries ceased in 1996, but the Montreal Protocol allowed eight developing countries that produce CFCs a grace period of 10 years. They began phasing out production in 1999 and it will cease completely by 2010. The grace period was necessary because new equipment is necessary for the substitute refrigerants. The cost of this equipment posed a problem for poor countries. Underdeveloped nations also agreed to freeze halon and methyl bromide production by 2002. Ensuring that developing countries comply is essential if the Montreal Protocol is to succeed. Money is always a form of assistance that developed nations can provide. The World Bank agreed to pay seven Russian companies $17.3 million to compensate them for ending production of CFCs and halons. The halt in production is being verified by outside experts who will continue to monitor the situation for some years. These Russian companies had accounted for half of the remaining production capacity. Sometimes, information alone is useful. In the case of halons, poor nations especially had the problem of ensuring fire protection while banning the very effective, safe, and affordable halons. The UN Environmental Program assisted by providing published case studies showing how this could be accomplished.

Box 8.3 | Reducing exposure to ultraviolet radiation

Recall from Chapter 2 that pollution prevention is preferable to treatment or control. Thus, banning ozone-depleting substances through the Montreal Protocol was a major achievement. However, quite aside from increased UV radiation reaching the Earth, even "normal" UV exposure needs to be controlled. Children, in particular, need sun protection because, by the age of 18, most will have been exposed to 80% of their lifetime dose of UV radiation – and the resultant later damage it can cause. Chronic effects of severe sunburn, or of overexposure even without sunburn, may not appear until many years later. In the northern hemisphere, people have a progressively greater need for eye and skin protection the further south they live, as the intensity of UV radiation increases. Despite all its negative effects, sunlight should not be entirely avoided and is necessary to form vitamin D in the skin. Individuals need exposure to sunlight for a few minutes a day several days a week. The sun also improves many people's sense of well-being, but protection is needed for anything beyond low exposures.

The US National Weather Service and the EPA provide a summer UV index used by newspapers, radio, and television in weather forecasts (Table 8.1). The index is calculated for noon, or 1.00 p.m. daylight saving time. The sunlight at 9.00 a.m. or 3.00 p.m. is only about half as intense as at noon. The higher the index value, the more quickly sunburn can occur. The further south a northern hemisphere person lives, the higher is the average index value. Light-skinned people, or those who sunburn easily, are most vulnerable. A high index should alert people to wear wide-brimmed hats, skin covering, and sunglasses that block 99% to 100% of UV radiation. Simple polo or T-shirts provide little protection to the skin. An unbleached cotton, high-luster polyester, or dark material is needed. Specialized fabrics are marketed to those with sun-sensitive skin. A sunscreen with a sun protection factor (SPF) of 15 or higher should be used. To protect against UV-A as well as UV-B, the sunscreen needs an ingredient such as avobenzone.

Substitutes for ozone-depleting chemicals

The major CFC substitutes developed were hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs). These alternatives still retain

Table 8.1 Weather service UV index

Index value	Exposure level
0–2	Minimal
3–4	Low
5–6	Moderate
7–8	High
9–10+	Very high

some ozone-depleting ability (about 10% as much as CFCs), and better substitutes are being sought. Interestingly, production of substitute coolants will be significantly lower than was CFC production because leak prevention has been improved and recycling is a given. This represents a significant change in society's approach to handling problem chemicals. Chemical substitutes have also been found for many industrial halocarbon solvents. ■ However, many farmers remain unhappy with the alternatives available for the fumigant methyl bromide. Because methyl bromide is also produced by the ocean, and forest and grass fires, some argue that the amount used by farmers is not great enough to warrant banning it. ■ Good alternatives to the fire-fighting halons are not yet available. Nonetheless, halons are banned because a 30- to 50-year supply remains on hand. Other fire-fighting substitutes evaluated either have undesirable properties or are very costly. For example, one iodine- and fluorine-containing chemical showed good fire-fighting properties and had a short atmospheric life, but was too toxic for routine use. Halon alternatives are still being actively sought.

Smuggling of CFCs and halons

The Montreal Protocol is largely a successful treaty. Levels of ozone-depleting substances in the lower atmosphere have begun a slow decline and may be stabilizing in the stratosphere. Unfortunately, some facilities continue to produce CFCs and halons illegally, and smuggling has became a serious problem. Contraband CFCs are used to recharge motor-vehicle air conditioners. Halons are still valued fire suppressors. For a while, CFCs were the second most lucrative commodity smuggled into the United States through Miami, exceeded in value only by cocaine smuggling. The trade slowed after North American, Japanese, and European authorities began to arrest and convict smugglers although these countries apparently remain the targets of smugglers. Much illegal trade moved to Asia. The origin of the contraband is presumably those countries that can still legally produce the CFCs until 2010, including India, China, Mexico, and Venezuela. Smuggling networks reportedly exist in India, Bangladesh, Pakistan, Malaysia, the Philippines, Vietnam, Indonesia, and other countries. Smugglers have many ways to disguise their actions. For instance, recycled CFCs can still be legally sold in developed countries. However, customs officers cannot tell the difference between the recycled and the new. Several ways to combat the illegal trade are in place. One is a 1997 amendment to the Montreal Protocol; this amendment set up a system of prior informed consent to control both imports and exports. Other means to fight the trade include providing direct financial assistance to certain facilities to end their production now and not wait until 2010 (see below). For CFCs at least, demand will abate as older cars are removed from the road. Nonetheless, illegal trade is seen as an ongoing threat, which could slow, even reverse, the recovery of the stratospheric-ozone layer.

Box 8.4 | Environmentally, there is no free lunch

CFC substitutes were selected on the basis of their effectiveness in serving desired functions, and on not having ozone-depleting ability. For some CFC uses, such as metal cleaning, it was fairly easy to find substitutes. It was less easy to duplicate the functions of CFCs as refrigerants or as an insulation foam in refrigerator walls. The HFCs and HCFCs finally selected are chemically related to CFCs, but have much less ozone-depleting capability. However, any chemical will have some environmental impact. As you read the examples below, keep in mind that all together these impacts are much less serious than stratospheric-ozone depletion.

■ HCFCs degrade more easily than CFCs, but do reach the stratosphere and have some ozone-depleting potential. Their manufacture will be phased out early this century. ■ HFCs have no chlorine and no ozone-depleting potential, but they are greenhouse gases and may eventually be banned for this reason. ■ The hydrocarbon cyclopentane can substitute for CFCs in the production of polyurethane foam insulation. However, it is a volatile organic compound (VOC) regulated by the US Clean Air Act.

■ Propellants used to replace CFC aerosols are flammable hydrocarbons, such as propane and butane, and should not be used near flames. ■ In leather shoe sprays, hexane and 2,2,4-trimethylpentane replaced the ozone-depleting chemical 1,1,1-trichloromethane, but incidents of acute respiratory illnesses have occurred among those using the sprays in poorly ventilated areas. ■ Water-based solvents replaced CFCs in many cleaning jobs, but the water necessarily becomes dirty. Although treated before release, inevitably some pollution is released into water bodies. ■ Some hydrocarbons can be used as refrigerants, but they are flammable – a major negative.

Innovative substitutes continue to be explored. Sound waves or thermoacoustic refrigeration could possibly completely replace chemical coolants as it needs neither refrigerants nor compressors. It combines evaporative cooling, already used in dry climates, with a desiccant to dry the air so the system can be used in moist climates. Most people would not consider eliminating refrigeration. As one public health scientist noted, "Refrigeration has done more to increase the life span of humans than pharmacology." People used to die of food poisoning caused by microorganisms that were able to multiply rapidly in foods kept at room temperature.

SECTION V

The future

A decline in CFCs and a return to normality

Together, CFC-11 and CFC-12 represent 50% of all CFCs used. Stratospheric levels of these chemicals increased until 2002 to what is expected to be their peak. Data supporting such a conclusion were gathered from monitoring stations around the globe, including the South Pole and Point Barrow, Alaska. However, the lifetime of CFC-11 is 40 years and that of CFC-12 is 140 years. Thus, stratospheric levels are expected to decline only slowly. In contrast, concentrations in the lower atmosphere already peaked in 1992 to 1994, and have declined since then. ■ The Antarctic ozone hole still appears each polar spring. Indeed, the year 2000 saw the largest ozone hole ever seen over Antarctica although scientists believe the depletion in 2000 was due to the unusual intensity of the Antarctic vortex (created by the circulating stratospheric air current separating polar air from the atmosphere around it). The UN Environment Program and the World Meteorological Organization make the projection that given full compliance with the Montreal Protocol, stratospheric-ozone levels will return to normal by about the year 2050.

Reducing CFC alternatives too

CFC alternatives are safer, but not environmentally benign; the next challenge is to reduce their use as well (Box 8.4). ■ HCFCs (hydrochlorofluorocarbons) are more reactive chemicals than CFCs, and thus have shorter atmospheric lifetimes and less capacity to damage ozone. Nonetheless, they have some ozone-depleting ability, and are also greenhouse gases. The Montreal Protocol required industrialized countries to cap their HCFCs consumption by 1996, and thereafter to progressively reduce their use: 90% by 2015, and totally by 2030. ■ Other substitutes, e.g., the HFCs (hydrofluorocarbons), became the alternative of choice to air-condition motor vehicles. HFCs don't contain chlorine and don't affect the stratospheric-ozone layer, but are powerful greenhouse gases.

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Chapter 9

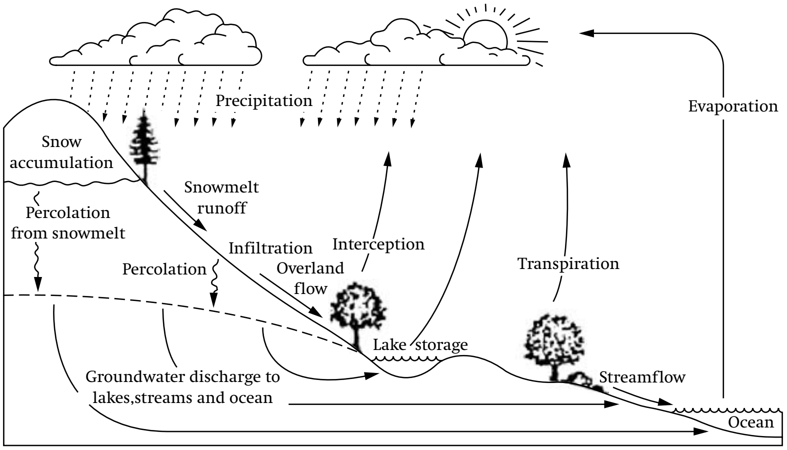
Water pollution

> "For change, we need three factors: leadership from above, pressure from below, or some exemplary catastrophe."
>
> *(Crispin Tickell, Oxford University)*

Aside from the very important issue of clean drinking water, why care about clean water? Clean water – and enough of it – is essential to any and all life, animals, plants, and microbes. Fish are vulnerable to polluted water. Indeed, there are places in the world where the water is so polluted that fish have disappeared. In many other places fish or shellfish survive, but are not safe to eat because their flesh is contaminated. Humans enjoy being around water, but contamination with infectious organisms makes swimming unsafe; or if water has obnoxious odors or scum, being near it is not pleasant. Clean water is vital.

This chapter surveys water pollutants, the problems they cause, and actions taken to reduce them. **Section I** introduces terms important to understanding water pollution. After then describing the six conventional water pollutants, it introduces toxic and non-conventional pollutants. **Section II** examines reducing point-source pollution, especially through wastewater treatment. Sewage treatment is a major part of this effort. **Section III** looks at the control and pollution-prevention methods commonly used to reduce sources of non-point-source pollution. **Section IV** examines how the impact of pollution differs depending on the type of water body affected (rivers, estuaries, groundwater, and wetlands). **Section V** delves into water pollution in a developing country, China. **Section VI** comes back to one conventional water pollutant, i.e., nutrients, and the major problems it is causing around the world. As you read this chapter, note whether a point or non-point source is being discussed. If it is a non-point-source pollutant, does it arise from land runoff or from atmospheric deposition? Learning the six conventional water pollutants first will make it easier to follow the rest of the chapter. Note

Figure 9.1 Movement of water in the environment. Source: New South Wales Environmental Protection Authority, Australia



Source: ANZECC & AWRC

too that three of the six conventional pollutants are implicated in global-level problems – pH (acid deposition), pathogenic agents (in drinking water), and nutrients (the "nitrogen glut"). As you familiarize yourself with water-pollution terminology, it is useful to understand how water cycles in the environment (Figure 9.1).

SECTION I

Introduction

Laws governing water quality existed in the United States before 1972, but there was no uniform national law. Water pollution was not well controlled and some states, eager to keep or attract industry, were negligent. The Clean Water Act of 1972 and the Safe Drinking Water Act of 1974 mandated states to treat water pollution uniformly. These laws have been updated over the years. Other countries likewise have laws to protect their water. Some enforce their laws well, but others poorly. In developed countries, many water bodies are cleaner than 30 years ago. When Congress passed the Clean Water Act in 1972, only 30% of US waters were judged fishable and swimmable. By 1994, it was greater than 60%. "Fishable" means that fish from the water are safe to eat; "swimmable," that it can be used for swimming without fear of infectious organisms or other unhealthy contaminants. Critics point out that the 60% figure may be deceiving. Although citizens may see improvements in specific water bodies, they cannot know the overall quality of the country's water bodies because large information gaps exist. In the United States, only 19% of rivers and streams are monitored and only 6% of ocean and shoreline waters. Methods used to monitor water also vary widely, and many consider the statistics unreliable.

Terminology

A “point source” is “any single identifiable source . . . from which pollutants are discharged, e.g., a pipe, ditch, ship, or factory smokestack.” Outlet pipes of industrial facilities or wastewater-treatment plants are examples of point sources. Developed countries such as the United States initially worked to control point sources of water pollution. Point sources originate in large easily identified facilities and thus are easy to trace. Developed countries control most point sources well. ■ A “non-point-source” pollutant is one whose source is much harder to identify precisely, hence the term “non-point”. ■ The word “runoff” indicates rainwater or snowmelt carried across land to water. Runoff arises from *non-point sources*. Runoff carries almost anything that water can carry – oil, grease, dirt, trash, animal waste, microorganisms, and chemical pollutants, including metals, pesticides, and fertilizers. *Urban* non-point sources include streets and parking lots, roofs, and construction sites.[1] *Rural* non-point sources include agriculture, logging, and mining sites. Pollution from non-point sources is much harder to control than that from point sources. ■ To better understand runoff, think of *watershed*. A “watershed” is a drainage basin encompassing an area in which rain and other precipitation drains into a particular river or river system. It also includes water bodies auxiliary to the river such as wetlands, aquifers, and estuaries. Basically, all precipitation falling in a watershed flows into one water body. This means that runoff from distant points can reach – and influence – the water body into which the river system flows, be it an estuary, lake, or wetland. ■ *Polluted runoff is the most serious water-pollution problem, a major problem worldwide.*

Box 9.1 | Pollutant movement in the environment

Categorizing pollutants as air, water, or soil pollutants is convenient. But a given pollutant often moves in land, water, and air. Sometimes it cycles among all three, and may contaminate food as well. ■ Once emitted into air, pollutants can settle onto water and land, including food crops and other vegetation. ■ If discharged to water or land, many pollutants become airborne, but then settle out again. ■ If deposited onto land, many pollutants run off into surface water; and, although partially detoxified by soil filtration, they seep down into groundwater.

Polychlorinated biphenyls (PCBs) provide an illustration of these movements. Most PCBs were initially discharged into water bodies or leaked into soil from equipment. PCBs, although not especially volatile, do become airborne from water and land. From air, they eventually settle again onto land and water, sometimes far

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[1] On undisturbed land, rainwater can percolate down through the soil to replenish groundwater. As the water moves downward, the soil – providing one of nature’s services – absorbs and detoxifies many pollutants. But on land covered with parking lots, roads, shopping malls, factories, buildings, and homes there is less soil to absorb water. In addition to less replenishment of groundwater, contaminant-carrying rainwater runs off into surface water.

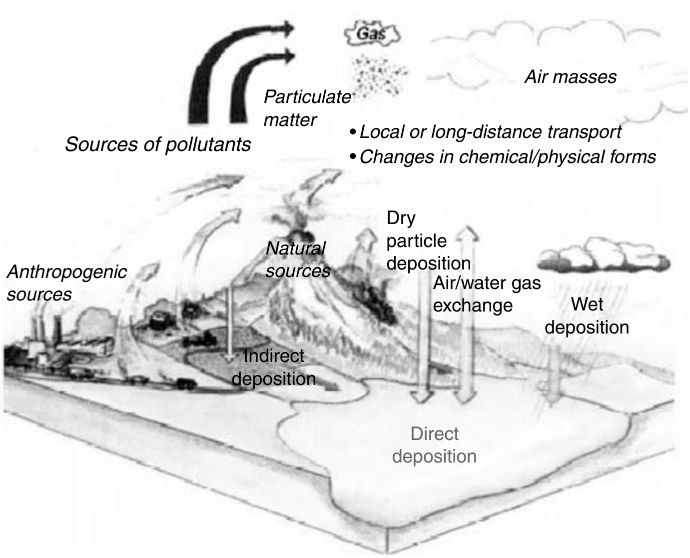

Figure 9.2 Sources and transport of atmospheric deposition. Source: US EPA

from their origin. From their new resting places, PCBs again become airborne, and the cycle continues to repeat itself.

Atmospheric deposition

Water is impacted by runoff from land, but it is also increasingly affected by another non-point source, i.e., atmospheric deposition (Figure 9.2). Acid deposition may be the best-known atmospheric deposition, but many other pollutants are also deposited from the atmosphere including nutrients, metals, organic chemicals, and microorganisms. To understand the significance of atmospheric deposition, reflect on the huge quantities of criteria pollutants emitted into the air: sulfur dioxide, nitrogen dioxide, lead and other metals, and particulate matter. The fate of these air emissions is often deposition onto Earth and water. Likewise, many airborne organic chemicals – pesticides, polychlorinated biphenyls (PCBs) and others – are also deposited onto land and water. Lake Superior, one of the Great Lakes, provides an illustration: about 91% of the PCBs in the lake come from the atmosphere; so do about 69% of the lead and 73% of the mercury.

Using this terminology

In 1985, European countries decided to reduce the excessive amounts of the nutrients phosphorus and nitrate running off into the Rhine River. They set a goal of reducing the amount of each nutrient reaching the Rhine by 50% within 10 years. They succeeded with phosphorus because it largely came from point sources – wastewater (sewage)-treatment plants. However, as you will see below, nitrate enters water bodies largely in non-point-source runoff. This is harder to trace and control. As of 2000, the desired 50% reduction in nitrate still was not achieved. ■ Now remember atmospheric deposition. This is another source of nitrate to water bodies (after atmospheric nitrogen oxide (NO_x) is transformed into nitrate and nitric acid, Figure 5.3). An example illustrates how significant atmospheric deposition of nutrients is: about 40% and 30%, respectively, of the nitrate input into Chesapeake Bay and the Potomac River basins is from the atmosphere.

Conventional pollutants

Pollutants regulated by the US Clean Water Act are described here. These are the "conventional," "non-conventional," and "toxic" pollutants. Just as the term "criteria air pollutants" did not reveal the seriousness of those six pollutants, the term "conventional water pollutants" does not tell us that these can have serious, even devastating, effects. However, "conventional" does correctly imply that these are common pollutants produced in large amounts. These conventional pollutants are as follows: *biochemical oxygen demand, nutrients, pH, suspended solids, oil and grease*, and *pathogenic microorganisms*. Note that none of these is an individual chemical. Indeed, one, microorganisms, refers to whole living organisms. These conventional pollutants will now be examined in turn.

Biochemical oxygen demand

Microorganisms decompose organic matter discharged to a water body. They require oxygen to do so. The amount of oxygen required to decompose a given amount of organic pollutant is the "biochemical oxygen demand" (BOD). Natural BOD, such as plant debris and wildlife feces, is almost always present. However, a high BOD often indicates human activity, such as sewage or industrial discharge. Human activities that lead to a discharge of BOD include municipal wastewater-treatment plants, food-processing operations, chemical plants, pulp and paper operations, tanneries, and slaughterhouses.

A high BOD can reduce or deplete the oxygen in water. In a large water body, fish can swim away from low-oxygen ("hypoxic") conditions, but crabs and snails and sedentary organisms may die. Professor R. Diaz of the College of William and Mary's School of Marine Sciences has noted, "Low oxygen now causes more mass fish deaths than any other single agent, including oil spills, and it ranks as a leading threat to commercial fisheries and the marine environment in general." Hypoxic water is a problem in the United States and worldwide. Hypoxia can be an irregular or seasonal occurrence in a water body, or an ongoing problem. An inorganic nutrient is not BOD, but notice in Box 9.2 that a nutrient can generate BOD.

Nutrients

A nutrient is a substance required for life, but has a more sinister face at high concentrations. Man-made fertilizers, containing concentrated *reactive nitrogen*[2] and phosphorus are a major source of nutrients to water bodies. When fertilizer is added to agricultural fields, the excess runs off with rainwater into water bodies. There water plants, especially algae, ingest the nutrients. This has a cascade of effects. Although synthetic fertilizer is the major offender, any organic matter has nutrient value. Human activities that lead to the discharge of organic matter include municipal wastewater-treatment plants, food-processing operations, chemical plants, pulp and paper operations, tanneries, and slaughterhouses. Natural sources of nutrients likewise are similar to those noted for BOD, i.e., plant and animal debris and wildlife feces.

Continuing input of excess nutrients can lead to *eutrophication*, a process "during which a lake, estuary, or bay evolves into a bog or marsh and eventually disappears." A water body naturally becomes eutrophic, but over many years as it slowly accumulates nutrients. During later stages of eutrophication, the water is choked with plant life, in particular algal "blooms." Blooms may form a scum on the water surface, produce offensive smells, give the water a bad taste, and make it unfit for swimming. Human activities that put excess amounts of nutrients into water accelerate eutrophication.[3] Nitrate and ammonia, as well as many organic chemicals, contain nitrogen in a form bioavailable to plants and algae. Excess nutrients – the "nitrogen glut" – have become a global problem. Section VI deals with this issue in more detail.

Box 9.2 | BOD and nutrients

Nitrate and phosphorus are two nutrients found in commercial fertilizer. As inorganic chemicals, they themselves do not exert BOD. However, they are fertilizers, stimulating plant growth.

- Nutrients stimulate algal growth in water, sometimes an algal bloom.
- Zooplankton eat the proliferating algae.
- Bacteria, using the oxygen in water to do so, digest the fecal pellets of the zooplankton as well as dead plankton and dead vegetation. Even if oxygen is only partially depleted, aquatic organisms suffer. If most of the oxygen is depleted, a dead zone can result.

In estuaries and coastal areas, excessive nitrate is the major culprit although phosphorus, another important nutrient, also contributes to the problem. In freshwater lakes, phosphorus is often the major culprit stimulating excessive growth of vegetation.

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[2] Reactive nitrogen is used in this text as a synonym for "fixed nitrogen" or bioavailable nitrogen. Atmospheric nitrogen is inert to most life. However, specialized microbes and a few plants can "fix" it into reactive or bioavailable chemicals such as nitrate. Fixed or reactive nitrogen can then be used by plants and algae to make nitrogen-containing biochemicals.

[3] The term "reactive nitrogen" is often referring to nitrate. When reactive nitrogen is present in larger amounts than needed, excess growth, especially of algae, is stimulated. The relatively more rapid growth of algae crowds out the growth of other plant life.

pH[4]

■ Acid deposition. You examined acid deposition in Chapter 6. Recall that the global problem of acid deposition can lead to water bodies becoming too acid to optimally support life or, sometimes, to support life at all. ■ Mining operations. These are another source of damaging amounts of acid. Metal ores often contain metal sulfides. Mining of sulfide ores and of sulfur-containing coal brings sulfides to Earth's surface. There, exposed to oxygen, sulfides are oxidized to sulfate, and in the presence of moisture sulfate is converted to sulfuric acid (Figure 5.2). This acid runs off into nearby water, sometimes causing great damage. To make the situation even worse, sulfuric acid dissolves metals, including hazardous metals, contained in mining wastes; rainwater runoff can carry these into water bodies. The acid damage can sometimes be carried for miles downstream. If iron is one of the metals present, contaminated streams can turn orange.

Suspended solids

This physical pollutant is found naturally in water to varying extents. As usual, it is an excess that is deleterious. Also recall that in air, it is the very fine particles which cause the greatest health problems. Similarly, fine particles in soil runoff become fine suspended solids in water, which can cause serious problems. ■ Increased suspended-solids content makes water more turbid or cloudy. This limits the sunlight reaching aquatic plants and stunts their growth. ■ Fine suspended solids can also clog fish gills and harm the respiration of other water animals. ■ Suspended solids can interfere with efficient water disinfection by shielding microorganisms from the disinfectant. Surviving microorganisms can then contaminate drinking water.[5]

A major *source* of suspended solids is soil runoff from agricultural fields, especially in row crops. Forestry and construction activities contribute too. Point sources of suspended solids are facilities that discharge various solids including those that create BOD.

Oil and grease

Oil spills are a major problem in some near-coastal waters, killing or adversely affecting fish, other aquatic organisms, birds, and mammals. These spills can also kill or reduce organisms living in coastal sands and rocks, and may kill the worms and insects that are food

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[4] Extremes of pH can be either acid or basic (alkaline). See Figure 6.2. Excessive acidity (low pH) is typically the major problem. However, excess alkalinity can also harm or kill aquatic life, such as when there is a spill of alkaline "liquor" from a pulp and paper mill using an alkaline pulping process.

[5] Soil particles that are not suspended can cause problems too. Heavier soil particles fall to the bottom of a water body. Eroded soil carried in runoff from agricultural lands and construction sites has badly impaired water quality in a number of rivers and lakes in the United States and elsewhere. Excessive soil input can suffocate or damage bottom-dwelling organisms, and change the characteristics of the water body. In the worst cases it fills in stream beds. It is a frequent cause of impaired water quality in rivers and lakes.

to birds and wildlife. When the spills intrude into coastal marshes, the oil can damage or kill fish, shrimp, birds, and other animals (Box 9.3). Oil spills can also foul beaches used for swimming and recreation. Despite the sometimes horrendous damage caused by oil spills, they are seen as a relatively minor problem for fish and the marine environment in comparison to chronic nutrient pollution. Depending upon the amount and type of oil spilled, where it is spilled, and weather conditions, ecosystem recovery can be quick or painfully slow.

Spills are not the only source of oil in water: oil leaking from vehicles, or released during accidents, washes off roads with rainwater and then reaches water bodies. A portion also percolates down to groundwater. Used oil from motor vehicles is often improperly disposed of too. Direct releases of oil into water bodies also occur. Motor and other recreational boats release up to 30% of their fuel, unburned, into water. These individually small, but ongoing events add up to much more oil than is spilled in a dramatic event such as the *Exxon Valdez*. However, the effects of a major spill are obvious whereas the environmental impact of ongoing small events is harder to assess.

Box 9.3 | The *Exxon Valdez*

In 1994, the biologist Rick Steiner described the effects of the Alaskan oil spill: "The essence of the disaster lies in images of once-playful river otters oiled and crawling off to die in rock crevasses along their home streams; bald eagles losing their grip in the treetops, falling dead, deep in the forest; orphaned sea-otter pups searching for dead parents, shivering through oiled fur in cold water that once seemed warm; seals, sea-lions, and whales staring up at a black surface through which they must swim in order to take their next breath, eyes and nostrils inflamed, often then inhaling oil instead of air; diving birds, soaked in oil and unable to fly, with simply nowhere to go but back into the thick of the oil. If nothing else, the *Exxon Valdez* should serve to remind all of us that any true prosperity we seek in this world must also include consideration for the many innocent beings along the way."[6]

Pathogenic microorganisms

Most microorganisms are not pathogens, and do not cause disease. Most perform useful, often vital, functions for humans including assisting the digestion in our intestines. We depend on microbes to degrade organic wastes in the environment and to biodegrade the organic material in landfills. We use microbes in fermentations to make food products, pharmaceuticals, and other chemicals. Microbes are almost ubiquitous in our environment, found almost anywhere that one looks. Professors Bruce Levin and Rustom Antia (see Further reading) state it well, "Almost every time we eat, brush our teeth, scrape our skin, have sex, get bitten by insects, and inhale, we are confronted with

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[6] Steiner, R. Oil-stained legacy. *National Wildlife*, **32**(5), August/September, 1994, 37.

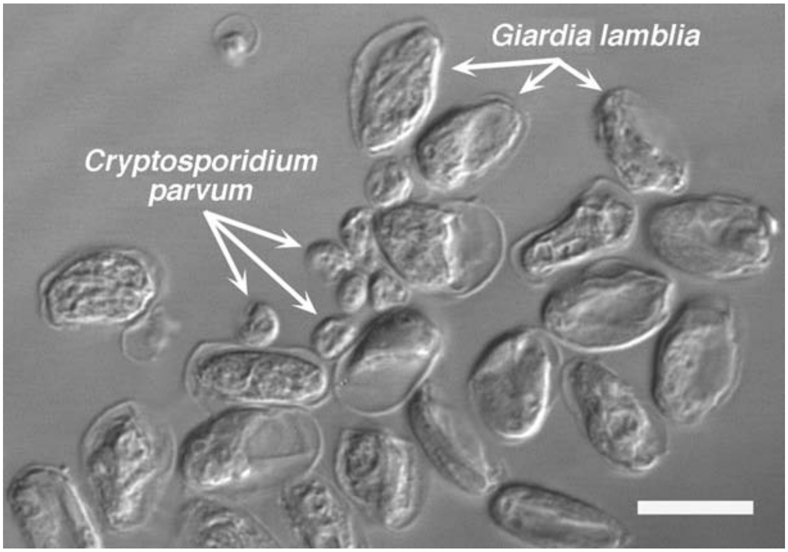

Figure 9.3 Two parasites in drinking water (*Cryptosporidium parvum* and *Giardia lamblia* from animal feces). Photo credit: H. D. A. Lindquist, US EPA (Scale bar, 10 µm). Source: US EPA Microbiology

populations of microbes that are capable of colonizing the mucosa lining our orifices and alimentary tract and proliferating in fluids and cells within us. Nevertheless, we rarely get sick much less succumb to these infections." It is specific microorganisms, pathogens that are capable of causing infectious disease, that concern us. A pathogen can be a bacterium, virus, fungus, protozoan, or toxic algal species.

Dangers of pathogens

Pathogens in drinking water, as we will explore in Chapter 10 are a tremendous health threat. Other threats posed by pathogens follow. ■ If infectious microbes or their toxins are found in shellfish, their harvesting for food use is halted. ■ Pathogenic viruses and bacteria in coastal water can infect swimmers and others. Viruses are abundant in marine waters, often surviving in salt water longer than bacteria. Infections can result not just by ingesting water containing pathogens, but through the skin. In the United States, as many as 19 out of 1000 swimmers each year are reported to suffer gastroenteritis caused by swimming in water containing infectious microbes.

Sources of pathogens

Pathogenic microbes in a water body are often anthropogenic, generated by human activities. ■ Runoff. They may arrive in water bodies in runoff of storm water, and from improperly operating septic systems, or runoff from livestock operations. ■ Point sources. Pathogens sometimes come from point sources, especially poorly performing municipal sewage-treatment plants. ■ All these sources exist in developed countries. The situation is worse in less-developed nations where most sewage remains untreated, and is often dumped into rivers and oceans. Figure 9.3 shows two pathogenic protozoans.

Priority (toxic) pollutants

If you remember that a specific pollutant, such as lead or chloroform, often contaminates more than one environmental medium, you won't be surprised to learn that many common air pollutants are common water pollutants too. Recall too that hazardous air pollutants (HAPs, Chapter 5) are often called toxic air pollutants. Likewise, priority water pollutants are often called toxic water pollutants. The US EPA, under the Clean Water Act, regulates 126 priority pollutants including metals such as arsenic, cadmium, lead, mercury, nickel, copper, and zinc. These metals are not only priority water pollutants. They are also HAPs (Table 5.4). Among the priority pollutants that are organic chemicals, are the widely used industrial chemicals such as benzene, toluene, and many pesticides. Many of these too are HAPs.

A high concentration of a priority water pollutant such as a pesticide may cause acute illnesses or death in aquatic life. In the United States, hundreds of fish kills are still reported each year that result from runoff of spilled pesticides or other chemicals. In smaller quantities, many priority pollutants present a chronic health risk, e.g., some pesticides may act as environmental hormones (Chapter 3).

If the priority pollutant comes from a point source, e.g., a wastewater-treatment facility, it can usually be well controlled. Control is more difficult for priority pollutants found in non-point-source runoff, as with pesticides from agricultural fields, organic chemicals in runoff from city streets, or polycyclic aromatic hydrocarbons (PAHs) deposited from air.

Banned discharges

The Clean Water Act totally forbids the discharge of some substances, including radioactive chemicals, and chemical and biological warfare agents. Other chemicals whose discharge is prohibited are PCBs, which in the United States are regulated by the Toxic Substances Control Act (TSCA). In industrialized countries, the manufacture of PCBs was banned in the 1970s, but they still occur in runoff from old spills, waste sites, or leaks in old electrical equipment. As a result of discharges into water when PCB manufacture was still legal, these long-lived chemicals are still to be found in sediments. PCB concentration is lower in water because of their poor water solubility.

Non-conventional and non-toxic pollutants

A third group of water pollutants regulated under the Clean Water Act is the non-conventional and non-toxic pollutants. Here we find ammonia, chloride (as from sodium chloride, salt), iron, aluminum, total phenols, and color. Many facilities – textile factories are an example – discharge colored effluents. The intensity of the discharged color is regulated by law. Heat is a regulated pollutant too. Electric power plants especially, but also many industrial facilities discharge heated effluents. Thermal pollution can cause problems but is not ordinarily as serious as many other pollutants discussed in this chapter.

SECTION II

Reducing point sources

One point source of water pollutant is municipal sewage-treatment plants and industrial wastewater-treatment plants. Wastewater is tap water after it has been used in homes, businesses, and institutions for drinking, bathing, flushing toilets, and other purposes (Box 9.4). Before a municipal or industrial facility can discharge wastewater into receiving water in the United States, it must first treat it to remove pollutants to levels in compliance with its particular permit. The intent of the US Clean Water Act was to eventually eliminate point sources of pollution. Because elimination was not immediately possible, the US EPA allowed permits to be issued to municipal and industrial facilities. These permits allowed discharges of specified amounts of particular pollutants. A facility must comply with its permit and regularly monitor its discharges to assure its compliance. The goal of permits is to limit discharges to a point that is protective of human health and aquatic life. Over the years wastewater treatment has become increasingly effective at removing contaminants, but pollutant release has not been eliminated. Unfortunately, in many less-developed countries pollutant release is poorly controlled or uncontrolled.

Box 9.4 | Sewer terminology

■ A "sewer" is an underground pipe system that carries wastewater to a treatment plant. ■ A "sanitary sewer" carries wastewater (from homes, commercial, industrial, and institutional establishments) to a treatment plant. ■ A "storm sewer" carries runoff from rainstorms or melting snow. ■ A "combined sewer" carries both sanitary wastewater and storm-water runoff. Combined sewer contents ordinarily go to a wastewater-treatment plant, but if a heavy storm exceeds the capacity of the system it overflows. The combined sewer overflow (CSO), containing untreated sewage and contaminated storm water, discharges into nearby water bodies. Combined sewers dating from the late nineteenth and early twentieth century remain in use in many hundreds of eastern and mid-western US cities. ■ Storm-water runoff, CSO, and other poorly controlled sewage systems have continued to lead to beach warnings or closings in coastal states. In the 1990s, the US EPA began to regulate or provide guidelines for storm-related events, not just for CSO, but storm drains that discharge directly to water, carrying pollutants and trash with them. These major and expensive programs will take time to implement effectively.

WASTEWATER
Primary treatment ⇓
PRE-TREATMENT
Aeration allows the release of gases such as hydrogen sulfide.
Physical methods are used to remove solid materials ⇒⇒Grit.
⇓
SEDIMENTATION
Suspended solids settle out ⇒⇒ Primary sludge.
Secondary treatment ⇓
BIOLOGICAL TREATMENT
Microorganisms digest organic substances in wastewater.
⇓
SEDIMENTATION
Mass of microorganisms is settled out ⇒⇒ Secondary sludge.
Advanced treatment ⇓
SPECIALIZED TREATMENT
This is sometimes used to remove remaining contaminants such as phosphorus or nitrogen.
⇓
WASTEWATER DISINFECTION
⇓
DISCHARGE OF EFFLUENT

Figure 9.4 Wastewater treatment process

Treating wastewater

Primary and secondary treatment

Initially, screens remove large objects such as sticks and trash from the wastewater, then smaller solids such as sand and small stones. Then, in *primary treatment* the suspended solids in the wastewater are settled out. Removing solids is the major purpose of primary wastewater treatment (Figure 9.4). Chemical treatment assists in settling out solids. Most BOD from the incoming wastewater settles out in the solids, as do many pathogenic organisms. Reactive nitrogen and phosphorus only partially settle out. After settling, solids are removed as *primary sludge*. ■ Wastewater then moves on to *secondary treatment*, where bacteria digest soluble organic contaminants. Because the bacteria multiply rapidly during this process, major quantities of microbes are produced and must be settled from the secondary wastewater, and recovered as *secondary sludge*. ■ The final step before discharging the wastewater is to disinfect it, typically with a chlorine-containing chemical (Figure 9.4).

Wastewater treatment typically removes only a portion of the phosphorus and reactive nitrogen, which can be so detrimental to receiving waters. Advanced treatment is necessary to remove all nutrients. Moreover, if standard treatment does not adequately remove the priority pollutants (described above), other treatment is necessary. Some wastewaters also need to have other substances removed such as those causing excessive color.

What to do with sludge

Large quantities of primary and secondary sludge result from wastewater treatment. In the past sludge was dumped at sea, landfilled, or incinerated. Dumping at sea is prohibited in the United States and a number of other countries. Landfilling is expensive. Europeans increasingly incinerate the sludge, but then they must still deal with the ash. ■ In the United States, 60% of treated sludge (called biosolids) is applied to farms, forests, parks, and golf courses as fertilizer. To meet standards for land spreading, sludge is sanitized to control pathogens. As necessary to meet legal standards, the sludge is treated to remove heavy metals and other contaminants. Lime may be added to raise the pH and reduce unpleasant odors. Many see sludge as a valuable biological resource that should be land spread. However, some raise major objections to the land spreading of sludge because it may contain surviving pathogens, metals, and organic chemicals such as PCBs and polybrominated diphenyl ethers (PBDEs). Sludge produces gaseous amines too. Concern is expressed for the workers spreading it and for those living nearby. One question raised is, could surviving pathogens be windborne to nearby communities from land-spread sludge after it dries? Communities near to land-spreading sites sometimes protest, fearing the sludge's contaminants, its odor, and the flies attracted to it. They assert that illness, even deaths, have resulted from the use of biosolids on nearby land.

Among developed countries, the United States has the least-strict standards for metals in sludge. US heavy metals standards are up to 100 times less strict than those of European countries. Europeans fear that soil may build up harmful levels of cadmium, zinc, copper, and other metals. This indeed sometimes happened in earlier years, especially in Eastern Europe. Europeans now consider how difficult, even impossible, it is to restore metal-contaminated farmland. Thinking far ahead they ask, what will soil metal levels be in 50 or even 500 years from now? Plant roots take up some metals such as cadmium from soil. Europe has such strict new standards for metals in food that even the low cadmium content now permitted in sludge would result in a cadmium level in wheat that would exceed standards.

In the United States, the US National Research Council reviewed the way that sludge was being handled, and proposed more research aimed at developing new standards. Some scientists support current standards. One US Department of Agriculture scientist stated, "We know more than enough to say with confidence that high-quality sludge can be used practically forever on farmland without any adverse effects." For their part, European scientists are reconsidering whether their standards are too strict. As continues to be pointed out on both continents, the sludge must go somewhere. We must develop treatments and standards with which people can be comfortable.

Industrial wastewater

In earlier years, industrial facilities often paid a municipal facility to treat their wastewater effluent along with municipal wastewater. This was financially attractive to municipal plants except that some industrial effluents had components that interfered with their proper functioning; or the municipal plant could not remove certain noxious pollutants and they passed into receiving waters. Municipalities often want to use wastewater sludge for beneficial purposes, and the presence of industrial pollutants can make that impossible. So, the US EPA began requiring industrial plants to pre-treat their wastewater before sending it to a municipal plant. Alternatively, some industrial facilities completely treat their own wastewater; it is then released to a waterway and not a municipal plant.

Alternative wastewater treatments

Wastewater can be treated in other ways. ■ Small communities with land available sometimes use artificial (constructed) wetlands. They direct wastewater to the wetland where suspended solids drop out. Nutrients are used by plants and microorganisms, which also often use or degrade organic chemicals. Metal pollutants are absorbed into the wetland soil, which obviously does not destroy the metals, but contains them in place. Even in cold climates, small communities can use constructed wetlands maintained in greenhouses. Some industrial facilities use constructed wetlands too, but they take up too much land to be feasible for large cities. ■ Recently, the French added chrysanthemums to the mix of plants in constructed wetlands. Aerobic (oxygen-dependent) microbes growing on chrysanthemum roots use the reactive nitrogen and phosphorus in wastewater as nutrients, taking up 40% to 80% of these from the wastewater. They reportedly remove 95% of the suspended solids too, and 91% of the BOD. Moreover, the chrysanthemums can be harvested and processed to obtain the natural insecticide *pyrethrin*, which is in high demand.

An attractive technology for small communities is a greenhouse with a complete ecosystem including slow-moving streams. It has flowers, ferns and other vegetation, and aquatic life such as fish, worms, and snails. After screening and grit removal, the wastewater is fed to bacteria, algae, zooplankton, and plants. These remove nutrients, reduce suspended solids and BOD, and otherwise carry out the functions of a wetland. The aesthetics are such that one author described it as having "the smell of a freshly tossed garden salad and the glassy look of a botanical museum." The effluent can be used for plant irrigation indoors and outdoors, for flushing toilets, and for groundwater recharge. Mature plants grown in the greenhouse can be sold.

Why deliberately pollute water with human waste?

Some think it strange to pollute clean water with human waste deliberately. Once dirtied, we must then cleanse that water, removing most of its solids and disinfecting it, before it is released to waterways. Such treatment of human sewage raises other problems too: ■ Treatment consumes large amounts of water, up to 30% of household water use. ■ Without special equipment, treatment plants discharge much reactive nitrogen and phosphorus, contributing to the excess nutrients in waterways. This is doubly unfortunate because urine is rich in nitrogen, phosphorus, and potassium. ■ Dealing with the sludge produced by wastewater treatment continues to be a problem. ■ *Micropollutants* (pharmaceuticals and their metabolites) found in feces and urine, enter wastewater-treatment systems, but many are not removed. Hormones, such as estrogens in birth-control pills are micropollutants of special concern. Especially in highly populated areas, enough estrogen reaches waterways below treatment-plant outfalls to affect fish and other aquatic life. Antibiotics are other micropollutants of major concern because they may contribute to the development of antibiotic-resistant bacteria in waterways. ■ As human populations grow, so do the problems associated with treating human waste. These pollution problems will not go away. Alternative approaches to handling human waste are needed.

Box 9.5 | A Swiss proposal

Are there better ways to handle sewage? ■ Few care for the "outhouses" once used. There are composting toilets, electric incinerating toilets, and a toilet combining the use of solar energy with composting. These toilets are used most often in vacation cabins. ■ Recently, Swiss scientists developed a technology called "NoMix", which they believe could be a substitute for the current toilet. It separates urine from feces. Only feces are carried to a central plant, and the urine is temporarily stored for separate collection or release. Their process uses 80% less water than now used to flush even a water-saving toilet. NoMix needs smaller wastewater-treatment plants and produces smaller amounts of sludge. Homeowners would save because the process saves water.

What about the urine? It could be sterilized, and its micropollutants and odor removed. Separate processing has advantages. Urine constitutes about 80% of the reactive nitrogen load and 50% of the phosphorus load to receiving water from a wastewater-treatment plant. Plants without expensive advanced treatment, have difficulty removing this nitrogen and phosphorus. Other interesting possibilities exist. (1) Current phosphorus production methods mean mining phosphate rock, a limited resource. Mining also poses environmental problems including the production of hazardous waste. And the phosphate rock recovered is high in cadmium, a heavy metal taken up by plants. (2) Producing nitrogen fertilizer involves fixing atmospheric nitrogen into a form that is bioavailable to plants, an energy-intensive process. To address both these issues, the Swiss propose to use urine as a rich source of both reactive nitrogen and phosphorus. And urine is a renewable resource.

Reusing wastewater

■ Individual households. "*Gray water*" is all the wastewater produced by households, businesses, and institutions, with the exception of sewage. It usually goes down the drain along with sewage and greatly increases wastewater volume and treatment cost. Some households in water-scarce areas now collect and use gray water. They can recover it by separate pipes, and use it to flush toilets, wash cars, or water yards. ■ Cities. Wastewater reclamation is a major issue in arid urban areas facing increasing water demand and often increasing populations. In reclamation, the treated wastewater is not discharged. Instead it is reused as cooling and process water, for commercial washing, ornamental fountains, fire fighting, golf-course irrigation, creation of artificial wetlands, and groundwater recharge. The major concern, but not the only one, is the surviving pathogens. However, if the reclaimed water is not used for drinking, pathogens need only be reduced, not eliminated. Some water-scarce areas embrace water reuse, but others caution that more monitoring is needed.

Limits to controlling point sources

Some point emissions have been reduced by 95%, even 99%. In the United States, by 1994 only about 15% of water pollution could be traced to point sources. But the original intent of the Clean Water Act was to eliminate discharges – the name of the permit issued to municipalities and industries was the National Pollutant Discharge Elimination System. Recall though how difficult it is to eliminate a pollutant end-of-pipe, even with very expensive treatment. A spokesperson for the Water Environment Federation, an organization of scientists, engineers, and wastewater managers, observed that many pollutants exist at levels so low that they are hard to quantify and often very difficult to eliminate. He stated, "It would probably cost as much to eliminate the last 5% of a contaminant as to eliminate the other 95% . . . Our philosophy is to move toward smaller amounts of pollutants and analyze the cost of eliminating decreasing quantities versus the benefit of the environmental gain." ■ Pollution prevention would, of course reduce the amount of pollutant formed in the first place. Some environmentalists suggest giving the most toxic pollutants a deadline by which time their discharge must be eliminated. The result could be societal phase out of the most toxic chemicals. This has already happened for some chemicals. An example is the international treaty banning 12 of the worst persistent organic pollutants (POPs). Another is the major decreases in lead and mercury emissions in developed countries using pollution prevention.

By the mid-1990s, US water quality was better than in 1970 despite a 25% increase in population and a 50% increase in gross national product. Yet point sources can still be significant, especially in urban areas. Maintaining a strong infrastructure is an ongoing problem. Municipalities have difficulty finding money to modernize or even properly maintain wastewater-treatment systems. Many struggle too with combined sewer overflow and storm-water management, still sometimes releasing untreated sewage during storms. Nationwide, modernization of treatment systems could cost hundreds of billions of dollars.

SECTION III

Reducing non-point sources

Reducing non-point-source pollution is much more difficult than reducing point-source pollution. Table 9.1 shows sources of polluted rainwater and snowmelt runoff, the contaminants, and ways to reduce them. A holistic watershed-protection approach is needed. But look at all the sources and consider how many people must take action to reduce runoff effectively – hundreds of thousands, millions of individuals must act. Is that possible? Author Cheryl Hogue[7] has said that, "Starting the clean-up of US rivers, lakes, and streams was easy. In the 1970s, nearly any action to control pollution yielded improvements in water quality. Now, commercial sources of pollution – those that are readily identified by effluent pipes – are fairly tightly controlled." The problem now "is in large part the result of runoff from roads and urban areas, farms, and timber operations . . ." In 2000, the EPA proposed that individual states develop plans to clean up waters polluted by non-point-source runoff. But the response was "a hailstorm of criticism from states, industry, agriculture, and the forestry sector and thousands of written comments to the agency." Such reactions make clear the difficulty of the task ahead.

On-site sewage systems

Wastewater-treatment plants are expensive to build and operate. Another major cost is building the pipe system connecting each home to the plant. To avoid these costs, homeowners and businesses in less-populated areas often build individual on-site systems. Underground septic systems are the best known of these. After treating household wastewater, these leave a concentrated *septage*, which must be periodically pumped out and treated. ■ Properly built and maintained on-site systems can treat waste in an ecologically sound manner and return the water to the environment. But improperly installed and maintained systems fail. Indeed, the US EPA estimated that at any one time 10% to 30% of septic systems are failing – these are a serious non-point-source of pathogens. The EPA is establishing new guidelines for septic system operation as follows. To ensure proper building and maintenance, a local government may track on-site systems. It may issue a permit to build a system, and require that it be periodically renewed. Before renewal the homeowner must show that the septic system has been properly maintained. Septage removed from septic tanks is typically transported to and treated at a traditional wastewater-treatment plant. However, similar to the alternatives described above, one alternative treatment takes septage to a greenhouse where it is aerated, heated, treated by bacteria, algae, plants and snails, and finally run through an engineered marsh.

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[7] Hogue, C. Clearing the water: EPA plan to address waterways that remain polluted. *Chemical and Engineering News*, **78**(11), 13 March, 2000, 31–33.

Reducing agricultural runoff

Agriculture is a major cause of non-point-source runoff of soil, pesticides, fertilizers, and animal wastes into rivers, lakes, and other water bodies.

- One important runoff control for many operations is to plant a buffer strip of grass or trees next to water bodies. These absorb runoff before it reaches the water.
- In no-till farming, crop residues are left on the soil, not tilled into the ground. It is an important means to limit soil erosion and runoff into water. A disadvantage is that more herbicide is needed to manage the weeds no longer plowed into the ground.
- Nutrients are typical, and very damaging, runoff contaminants. Farmers ordinarily apply more fertilizer than is needed to their crops. Crops cannot capture or use it all. When it rains, the excess runs off into surface water or percolates down into groundwater. In some instances, agricultural specialists work with farmers to analyze land nutrient needs, section by section, and enter the results into a computer within a tractor. The computer lets the farmer know whether a particular section actually needs fertilizer before any is applied. Less fertilizer applied means less fertilizer runoff into water.
- Farmers can minimize pesticide runoff by using "integrated pest management" (IPM). In IPM, farmers evaluate their fields regularly, using a pesticide only as necessary, when a pest population reaches a certain level. This contrasts with the still often-used method of applying pesticide according to a schedule, regardless of need. Reduced applications mean less pesticide in runoff from treated fields.
- When researching new products, chemical companies now place priority on developing herbicides that can kill weeds in much smaller amounts. Newer herbicides are also often less water soluble and bind more tightly to soil – both these characteristics can lower pesticide runoff.
- Facilities with large numbers of animals often produce runoff containing animal waste, which has contaminated both surface and groundwater with potentially infectious bacteria, viruses, or protozoa, especially *Giardia* and *Cryptosporidium*. There are methods to minimize runoff (Table 9.1), but even some mammoth operations do no more than allowing waste solids to settle out in a detention pond. Pollution-prevention approaches would include a return to smaller family farms with fewer animals at one locale, and eating less meat.

Reducing agricultural runoff is a major challenge. Farmers need to be willing to educate themselves on methods to control or reduce runoff. This can mean significant changes in the way many farm, requires more time, and often involves additional costs. Providing incentives or assistance can make a difference. One cooperative

Table 9.1 Reducing non-point-source pollution to rivers, lakes, and coastal waters

Sources and pollutants produced	Reducing or treating the runoff
Agriculture (growing crops) Contaminants include soil, fertilizers, pesticides (if irrigation is used, salt is in the runoff too)	• Trap runoff by a *buffer strip* of vegetation next to water bodies • Use *no-till farming* to limit soil erosion • Use *precision farming* to reduce fertilizer use • Use *integrated pest management* (IPM) to reduce pesticide use and runoff
Agriculture (animal operations) Contaminants include animal wastes with pathogens, nutrients, BOD, suspended solids	• Use *barriers* to prevent leaks from lagoons • *Treat* feces/urine from factory farms • Limit factory farms; encourage family farms
Timber-cutting operations Contaminants include soil, BOD, nutrients	• Leave a *buffer strip* of uncut trees near streams to absorb runoff • Build logging roads to minimize runoff • Build *wetland* to capture and treat runoff
Mining operations Contaminants include acid (sometimes severe), soil, metals	• *Grow vegetation* on sites to retain soil and pollutants, or *seal mine* as permanent solution • For strip mines, restore polluted water and damaged land
Construction sites Contaminants include soil, oil/grease, heavy metals, debris	• Build *settlement (detention) pond* to trap runoff • Put hay dam or fabric fence around the site • Lay out construction site to *follow land's natural contours* or modify its contours
Cities/suburbs with sealed surfaces (roads, parking lots, malls, roofs, etc.) Contaminants include oil, grease, metals, PAHs (from motor-vehicle exhaust), salt, sand, bacteria, eroded soil, animal wastes, and debris. • 99.9% of water hitting paved or roofed surfaces runs off into storm drains	• Put in *green strips* (vegetation); this slows down and helps clean rainwater (further cleansed as it seeps to groundwater) • Re-sculpt streets to *direct storm runoff into vegetated road margins* (not storm drain) • Use *infiltrators* under parking lots to collect and partially clean storm water and allow it to percolate to groundwater; or, trap runoff in detention ponds (mini-wetlands) • Use *wetlands* to store floodwaters. After major 1993 US floods in the mid-west, some levies were torn down and wetlands *constructed*

venture between Wisconsin dairy farmers, the University of Wisconsin, and the US Department of Agriculture provides an example of reducing runoff of pesticides, fertilizers, and eroded soil to waterways. University Cooperative Extension Service consultants visited participating farms each week of the growing season over 3 years. They worked with farmers to monitor pest populations in the crops grown to feed cows, with the intention of limiting the number of pesticide applications. They encouraged farmers to plant nitrogen-fixing legumes to enrich the soil, thus reducing the need to apply artificial fertilizer. ■ Farmers did reduce their use of pesticides and fertilizers and reduced contaminated runoff. Participating farmers also saved several dollars for each dollar invested; 80% of the farmers continued using these methods even after the program ended. However, many farmers do not use equivalent methods, and many surface water bodies and groundwater continue to have high, sometimes growing, reactive nitrogen levels. The situation is worse in the more-populous Europe than in the United States. It is especially bad in Asia where attention is focused on the more immediate problem of producing enough food for growing populations.

Reducing non-point-source runoff from other activities

Notice in Table 9.1 that many sources of runoff have similar means of control. Providing buffer zones of grass or trees near water bodies into which runoff can flow is a control mechanism common to many sources of runoff. Building detention ponds or constructed wetlands is also common to several sources. Some methods are unique to a specific source, such as sealing off an open mine that is the source of runoff. Pay special attention to the methods in Table 9.1 that represent pollution prevention (P^2). P^2 is always the first option – prevent the pollutants from being formed. For large construction sites or logging roads this may mean laying out the sites in a way that uses or modifies the land's natural contours to reduce runoff.

Other non-point sources

Table 9.1 is not comprehensive. Two additional sources of non-point-source pollution are runoff produced by excessive water use, and non-point-source atmospheric deposition.

Excessive water use

The EPA notes that, "The high demand for and overuse of water can contribute markedly to non-point-source pollution . . ." This happens in several ways. ■ When farmers use more water than necessary to irrigate their land, this increases runoff carrying with it sediment, nutrients, and salts. ■ Individual overuse of water to maintain yards and gardens increases runoff too, carrying soil, nutrients, and pesticides. ■ When households with septic systems overuse water, this contributes to system failure with resultant non-point-source runoff carrying microbes including pathogenic agents.[8]

Atmospheric deposition

Atmospheric deposition has become an important non-point source. Methods to reduce it are often specific to a given pollutant, and are referred to throughout this book. Reducing acidic deposition, for example, was discussed in Chapter 6.

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[8] For more information, see the US EPA web site, http://www.epa.gov/OW/you/chap2.html, on How Excessive Water Use Affects Water Quality.

Questions 9.1

1. Pollution prevention (P^2) is preferred to control of runoff. (a) Examine Table 9.1 – what are four examples of P^2 given in this table? (b) What are four examples of control or treatment?
2. How can communities motivate homeowners to reduce non-point-source runoff from their properties?
3. What are two water-pollution issues that are worsened, or made more difficult to deal with, because of population growth?
4. Human error, bad weather, and crowded harbors contribute to continuing oil spills along coastlines. What are two ways that P^2 could be used to reduce oil spills?

SECTION IV

Impact of pollution on water bodies

When thinking about the impact of a pollutant, be sure to consider the type of water body involved: a river, lake, stream, wetland, estuary or coastal water, ocean, or groundwater. ■ A given quantity of pollutant running off at one time into a large fast-running river may have minimum impact, but the same amount may damage a slow-moving stream or small lake. Of course, if the pollutant continues to enter the large river, it too may be damaged. *Or* a river may carry continuing inputs of pollutants to locales where they do cause damage – as happens with the dead zones described below. Metals are natural components of sea water, and a one-time small additional input may go unnoticed. But, adding the same amount to a fresh-water lake, where metal concentrations are normally low, may cause problems. Lakes also may have little exchange of water to dilute the metal. Of course sea water too, especially coastal water, may be badly polluted by continuing input. ■ If you add an organic pollutant to surface water, microbes may break it down, assisted by oxygen, sunlight, and wave movement, or it may evaporate. Conversely, groundwater has fewer means to degrade these pollutants, and hence their impact is more severe.

Coastal pollution

"Everything we do on land ends up in the ocean." About 80% of coastal and estuary[9] pollution arises from rainwater and snowmelt runoff,

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[9] An estuary is the locale where a river reaches the ocean. It is an intertidal zone containing partly fresh and partly salt water. An example is the region where the Sacramento and San Joaquin Rivers empty into a delta on the San Francisco Bay. Many estuaries have been much modified by human activities. At one time, before massive human modification, this delta was a great maze of channels, wetlands, and ponds, which supported tremendously prolific life.

and atmospheric deposition. Both these deposit a great variety of pollutants, often great quantities as well. Historically, oceans seemed infinitely able to accept anything that we dumped into them. They diluted and dispersed pollution of all kinds. But as human population grew, especially coastal population, and human activities grew too, coastal waters became increasingly unable to cope with massive pollutant inputs. Fisheries and other coastal resources important to humans have degraded. Wildlife and bird populations have decreased due to ongoing destruction of habitat by development, but also due to pollution. Worldwide about two billion people, a third of humanity, lives within a hundred kilometers of a coastline. And increasingly the world's people live in megacities – cities with a population of 10 million or greater; 13 of the world's current 19 megacities are coastal.

Nutrients

Nutrients have become a major coastal-water pollutant. Consider the results of an 8-year study. It reported that coastal inputs of reactive nitrogen had increased 3-fold in North America, 6-fold in Europe, and 11-fold in Europe's North Sea. You need only recall, "the dose makes the poison," to think that such sharp increases may have adverse effects. Fertilizer runoff is the major source of this reactive nitrogen (as nitrate) pollution, both from upstream runoff into rivers and coastal activity. Air deposition of nitrate is also important; it too can come from afar. Sewage nutrients are a third source. The United States alone produces 10 billion gallons (37 billion liters) of wastewater each day and – although most sewage is treated – 85% of the effluent flows into estuaries and bays. In areas near large cities, in particular, this can be a problem.

Fecal contamination

About one-third of US shellfish beds are closed to harvesting because of contamination with fecal microorganisms or with algae that produce toxins. ■ Pollution plays a major role in closing beaches for swimming and, in 1998 resulted in the closing or posting of advisories at 1500 US beaches (Figure 9.5). To reduce coastal pollution, the United States bans ocean dumping of sewage sludge, treated or not, and industrial waste. Large coastal cities must also have stormwater discharge permits. Nonetheless contamination continues. The US EPA is working with states and cities along the marine and Great Lakes coasts to reduce pollution so that once again there can be shellfish harvesting, fishing, and swimming. US municipalities are also beginning to meet stricter combined sewer overflow regulations that prevent untreated sewage from flowing into water.

Other pollutants

Many other pollutants also threaten coastal waters. Metals and many organic chemicals have increased. Oil spills are a special problem. The US Oil Pollution Act of 1990 requires double hulls for new or

Figure 9.5 Sewage contamination can affect swimmers. Source: US EPA

upgraded oil-carrying vessels, and safe transport is a priority for some oil companies. Nonetheless, spills continue because of human error, bad weather, and crowded harbors.

Less-developed countries

Problems are sometimes far worse in impoverished countries. One major reason for this is the fact that only a few per cent of an increasing flow of human waste is treated. Coastal pollution and degradation is one of the more-serious problems that humanity faces.

Protecting coastlines

You can see that protecting the marine environment from land-based activities is enormously challenging. The United Nations initiated a program in 1995 involving several of its own agencies (Table 9.2) and the governments of 108 countries. Its first task was to understand the contaminants and activities contributing to coastal pollution and degradation. It established a clearing house to make scientific and technical information easily available to those that need it, and to provide information on financial resources available to help nations attack coastal pollution. Just one effort, among many to reduce coastal pollution, is the ban on 12 persistent organic pollutants (POPs) instituted through the Stockholm Convention of 2000.

Demonstrating reduced pollution

Preventing or controlling the release of pollutants can demonstrably reduce environmental pollution. To illustrate this, recall that the United States banned DDT and PCBs in the 1970s and strictly reduced the use of the hazardous metal, lead. It also much reduced emissions of combustion pollutants including metals and PAHs. Now consider a project of the US National Oceanic and Atmospheric Administration

Table 9.2 UN Global Program of Action for the Protection of the Marine Environment from Land-Based Activities (http://www.gpa.unep.org/about/tag10)

Issue	Principal UN agency
Sewage	World Health Organization http://www.who.int/en/
Oil and litter	International Maritime Organization http://www.imo.org/home.asp
Nutrient and sediment mobilization	Food and Agriculture Organization http://www.fao.org/
Heavy metals	UN Environmental Program http://www.grid.unep.ch/
Persistent organic pollutants	UN Environmental Program
Radioactive substances	IAEA International Atomic Energy Agency http://www.iaea.or.at/
Physical alterations to the coast	UN Environmental Program

(NOAA), which measured chemicals in mussels and oysters at 240 US coastal sites in 1995. As compared with 1984, NOAA found lower, sometimes dramatically lower, levels of contamination of shellfish. Reductions occurred for the banned chemicals and for combustion pollutants including PAHs and metals. ■ NOAA did not test shellfish in areas known to be highly contaminated. However, the US Food and Drug Administration (FDA) studied seafood contamination at a "hot spot" (heavily contaminated area) about an hour's sailing time from Boston. This spot had become heavily contaminated with PCBs and other chemicals that were dumped there for many years prior to 1976. In 1992, the FDA collected lobsters and many fish at this spot including cod, flounder, and ocean trout. It tested them for PCBs, PAHs, heavy metals, and pesticide residues. Pesticide residues were found in only a few samples. PCBs were not detected at all in half the samples and the rest had only trace amounts or levels within acceptable FDA limits. This was also true of cadmium, mercury, lead, and arsenic. So 16 years after the dumping ceased, an FDA spokesperson was able to say, "This snapshot concludes that the overall residues are low and the seafood from Massachusetts Bay is safe to eat." ■ The NOAA and FDA studies show that contamination decreases after polluting activities are eliminated or decreased. However, high concentrations of PCBs and other chemicals still survive in sediments at hot spots around the Great Lakes, marine coasts, and some rivers.

Grading US estuaries

These encouraging NOAA and FDA results showed real benefits from taking action to reduce pollution. A less-benign picture emerged from a broader study done by the US EPA, which in 2002 issued a report card on US estuaries.[10] Although the report rated the ecological condition of 56% of the estuaries as good, 44% were graded as unfit for aquatic life or for swimming. The EPA reached its conclusions on individual estuaries using a variety of indicators. It looked at water

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[10] US EPA. 2002. EPA Report on Estuary Quality. http://epa.gov/owow/oceans/nccr/chapters/chap9future.pdf (accessed January, 2004).

quality: How clear was the water? What was its dissolved oxygen content, and thus ability to support life? Was the water eutrophic, i.e., able to support harmful algal blooms? The EPA also examined estuary sediments as well as the tissues of fish living in the estuaries: To what extent were these contaminated with metal and organic pollutants, and microbes? In addition, the agency appraised how well each estuary's coastal wetlands supported plant and animal life. It also evaluated the variety, numbers, and health of fish, shellfish, and waterfowl living in the estuary. The EPA also examined the causes of estuary pollution, and obtained results similar to those described above for coastal pollution. Preventing further deterioration of these estuaries is a major challenge. Box 9.6 describes the difficulties of restoring the Chesapeake, a major Bay. We are forced to conclude that if human population and development activities continue to increase, we will be confronted with ever-larger challenges.

Box 9.6 | The US Chesapeake Bay

There are 150 rivers and streams, from 6 states and the District of Columbia, feeding into the Chesapeake Bay. The estuary created is the largest in North America. The Chesapeake Bay like many others once had flourishing ecosystems and was a major source of fish and other seafood. But, as human population and industrial activity increased over the decades, water quality deteriorated. Fish and oyster populations dropped as much as 80%. The underwater grasses vital to coastal life disappeared. ■ The major pollutants affecting the Bay are nutrients, metals, organic chemicals, and microbes. The most severely polluted areas are around urban centers, but the whole bay is affected.

Taking action

With EPA support, a Chesapeake Bay Commission began working with the affected states to develop control and pollution-prevention strategies to protect and restore the estuary and adjacent coastal waters. Reducing non-point-source runoff was the chief challenge. ■ One major goal was to reduce by 40% the runoff of reactive nitrogen and phosphorus into the bay. To do this, farmers would be trained to reduce runoff by altering the ways they applied fertilizer, and managed manure and sludge. ■ To reduce pesticide runoff, farmers and other pesticide users would be enrolled in integrated pest management programs. ■ To reduce the bay's microbial contamination, wastewater-treatment plants would be upgraded, and millions of home septic systems controlled. ■ Other strategies were developed to reduce the input into the bay of 14 high-priority toxic chemicals. ■ Another program was to develop forest buffers along river banks to absorb runoff contaminants. Early results were encouraging. Forest buffers were planted, and industrial releases of toxic pollutants were reduced. Underwater grass beds began to rebound, and more striped bass were found in the bay.

A stalled restoration

Each year, 13 indicators are assessed for the bay including: wetlands, forest buffers, underwater grasses, toxic pollutants, nutrients, water clarity, dissolved oxygen, and populations of crab, rockfish, oyster, and shad. Unfortunately, by 2001 human population growth, sprawling development, and an associated loss of farmland and open spaces had stalled restoration. The 2001 US NOAA State of the Bay Report (see NOAA Report in Internet resources) noted a decline in blue-crab population. There were more algae and increased sediment, both blocking the sunlight needed by underwater grasses, and smothering fish and shellfish. The report stated, "the bay remains a system dangerously out of balance. The Chesapeake operates at little more than one-fourth of its potential because water pollution, primarily from excess nitrogen and phosphorus, inhibits overall improvements to the system." ■ For the bay to thrive again, nitrogen and phosphorus need to be cut in half. But a lack of funding has prevented upgrading of sewage-treatment plants to allow better trapping of phosphorus and reactive nitrogen. And lack of farm subsidies for conservation programs has allowed continuing high nutrient runoff from farms. Excess nutrient input also continues from homes and home septic systems. ■ Microbes continue to enter the bay too from improperly treated sewage and septic systems, and in runoff of animal waste. ■ Metal and organic pollutants, although reduced, continue from industrial point sources and urban runoff.

A score of 100 represents the pristine bay existing before European settlement. In 2001, the score was 27, not much better than the 23 seen in 1983, the year the bay "bottomed out." In 2000, a coalition of federal, state, and local officials signed a new agreement pledging action to increase the score significantly. One official stated, "We will never again see the Chesapeake restored to its pristine state of four centuries ago, but we believe a bay with an index of 70 is achievable by 2050. We must remember how rich our Chesapeake Bay was, even 40 years ago, and not settle for a small fraction of what we know it can be." The Chesapeake Bay illustrates the difficulty that even a wealthy country has in restoring and maintaining a healthy environment.

Groundwater[11]

Groundwater is a vital resource on which more than one-quarter of the world's population depends for drinking water, more than 50% in the United States. When groundwater is very deep, runoff contaminants may not reach it. However, much groundwater used for drinking is in shallow aquifers. Moreover, there is close connection between shallow groundwater and surface water, so groundwater pollution can pollute adjacent surface water. Once polluted, groundwater can stay so for a very long time. ■ Compare an organic pollutant in groundwater to one in surface water. Groundwater has fewer microbes to digest organic pollutants, less oxygen, no sunlight, and no surface from which organic pollutants can evaporate. Especially in slow-moving groundwater, pollutants may persist indefinitely. Organic

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[11] Groundwater is found beneath the Earth's surface in aquifers (porous geologic formations). Sometimes groundwater flows in a channel, but not usually like a surface stream. Rather the formation is composed of permeable rock, gravel, or sand that is saturated with water. Groundwater can flow, but ordinarily more slowly than surface water. On the other hand, groundwater sometimes supplies above-ground springs and wells.

Table 9.3 Groundwater contamination sources[a]

Source	Contaminant
Landfill (improperly built or maintained), old dumps, unsecured hazardous-waste sites	Water-soluble chemicals in trash (metals, salts, some organic chemicals)
Septic systems (poorly built or maintained)	Microorganisms including pathogens
Farms, grassy areas (lawns, golf greens, etc.)	Fertilizer (nutrients) and pesticides
Livestock farms	Nutrients and microorganisms leached from feces
Surface spills	Oil, hazardous chemicals, etc.

[a] Groundwater is frequently used for drinking water, so humans may be exposed to these contaminants. In addition, groundwater often comes into contact with surface water in many places, streams, rivers, lakes, allowing contaminants to reach surface water. Information source: US EPA (http://www.epa.gov/ogwdw/protect/assessment.html).

chemicals, such as certain oils that have low water solubility pose special problems. Trapped in soil and rock below and around the groundwater, they continue to slowly leach into water maintaining contamination indefinitely. Metals of course don’t degrade, but may become tightly bound to the soil.

How groundwater is contaminated

Surface pollutants, dissolved in water, percolate down through the soil. Shallow groundwater, that closest to the surface is most easily contaminated. How much pollutant reaches groundwater depends on soil type, pollutant characteristics, and the distance to groundwater. Contamination sources (Table 9.3) include many types of runoff, agricultural and urban, chemical spills, and landfill leachate – anything that may percolate through the soil into groundwater. Pathogens, especially viruses which are very tiny, can percolate into groundwater too. Thus, sewage from improperly installed or maintained septic systems and confined-animal operations can contaminate groundwater. Nitrate also reaches groundwater. Petrochemicals from leaking underground storage tanks can contaminate too. And groundwater often has detectable levels of pesticides. Detectable does not necessarily indicate a problem, but does indicate a need for ongoing monitoring and efforts to prevent further pollution.

Reducing groundwater contamination

Because surface water and groundwater are often closely interconnected, runoff can contaminate both, and a holistic approach to protection is necessary. In the United States, the EPA has worked with states to develop pollution prevention (P^2) strategies to protect watersheds that feed aquifers and wellheads. A “wellhead” is the immediate area around a public water supply intake, a more limited area than a watershed. An example of how P^2 can help maintain groundwater purity is regulations specifying which pesticides can be used in a wellhead area (those with little tendency to migrate into groundwater) and specifying how to apply pesticides so that little runoff results. Another P^2 approach is regulating how land can be used: prohibit landfills or gasoline stations over groundwater that feeds into the wellhead; prohibit large confined-animal operations near vulnerable groundwater, or even prohibit farmers from grazing livestock there. ■ Sometimes, as with hazardous-waste sites, the pollution already exists and only control is possible: block waste-site pollutants from reaching groundwater. If the groundwater is already contaminated a barrier can sometimes be inserted into the ground to prevent further migration of the pollutant, especially if the groundwater is shallow.

Cleaning up groundwater

Once polluted, groundwater is extremely costly to clean up. Clean-up is often not feasible with today's technology, although *pump-and-treat* is commonly used with the goal of restoring the water to drinking quality. Water is pumped to the surface, treated to remove pollutants, and then returned to its source. Especially in aquifers with large volumes of water, pump-and-treat may continue for many years and not notably reduce pollution. An US National Academy of Sciences panel, after extensively studying pump-and-treat, concluded that some sites would not reach drinking-water quality even if treatment continued for 1000 years. It advised against routine use of pump-and-treat and instead recommended containing the contaminated water in place until effective treatment technologies become available. Containment involves building an underground structure to prevent the contaminated water from migrating off-site. However, this works only for shallow water that is contaminated within a containable locale.

Sometimes groundwater is treated *in situ*; that is, it is not removed from the aquifer. One such technique involves installing tons of iron filings mixed with sand in the path of the contaminated groundwater. Some organic pollutants, trichloroethylene is one, react with the iron as the water flows through this permeable barrier and decompose into benign products. Another technique being explored is to find anaerobic microorganisms (those not needing oxygen) to degrade the contaminants *in situ*. Because groundwater has too little oxygen, aerobic organisms (those that need oxygen) cannot be used.

Wetlands

Wetlands include: coastal and inland swamps, bogs, and marshes. One of the natural services that wetlands provide is sequestering pollution. Thus, the fact that an estimated 50% of the world's wetlands have already disappeared represents a major loss in pollution control quite aside from the natural functions of wetlands. Also, although wetlands can be excellent buffers against pollution, they too can become contaminated enough to harm the animals, plants, and microbes that live within them.

Questions 9.2

1. Consider several facts. ■ The population of southeastern Michigan may grow by 6% in the coming 20 years, but the amount of developed land will grow by 40%. ■ Nationwide, over the past 40 years, the average number of people in a US household declined from 3.6 to 2.7. This increased the number of households. ■ The number of vacation homes in the United States is increasing. ■ The amount of shopping space per person is increasing, usually as more shopping malls. How do these activities lead to increased water pollution, air pollution, and land pollution?
2. Environmental degradation can be a major urban problem. At the same time, one person living in a large city such as New York can exert a lower environmental impact and produce fewer pollutants than a person in a suburb. How?

SECTION V

Less-developed and developing countries

You have already seen instances of water pollution in less-developed countries, as noted in Box 1.5, A letter from India. In this section, China, which has the largest population in the world and rapid economic growth and development often occurring at the expense of its environment, will illustrate the water-pollution problems of a less-developed country.

China's water pollution

Reports from the UN Food and Agriculture Organization, the World Bank, the World Resources Institute, and China's State Environmental Protection Administration (SEPA) stress the gravity of China's environmental degradation. Water pollution is severe; 80% of 50 000 km (31 000 miles) along its seven major rivers, including the Yellow and Yangtze, are so badly polluted that they no longer support fish life. Some fish species have become extinct, taking with them a valuable food source. Pollution is especially severe in the industrial north. In substantial portions of the rivers, pollution has been so bad that it is unsuitable even for industrial use let alone for irrigation or drinking water. Many river sections are classified as unsuitable for human contact. A drought has worsened the pollution in recent years because the same amount of pollution enters the rivers, but there is less water to dilute it. Lakes and coastal areas are also badly polluted.

Water pollutants include hazardous metals and organic solvents from oil refineries, chemical plants, paper mills, and other facilities. Agricultural runoff, untreated human sewage, and animal waste lead to excessive nutrients, excessive BOD, excessive suspended solids, and microbial contamination in rivers. Water-pollution reports use terms such as “ever-deteriorating conditions” and “unsuitable for human contact.” Diseases from bacterial pathogen contamination are “epidemic.” One Chinese observer said, “You cannot find a single river that is clean these days in China.” In addition, more than half of the groundwater is severely contaminated. Coastal waters are rated as poor or, in some places, worse. China has a water-scarcity problem too, made worse by the fact that so much of the water is polluted.

Why water pollution is so severe

China’s population is about 1.3 billion, and continues to grow along with increasing industrialization and urbanization. China’s economic growth rate in 2000 was 7%. The government is struggling to at least stabilize its environmental problems including water pollution. In 1995, China produced 37 billion tons (34 billion tonnes) of municipal and industrial wastewater. Although 77% of the industrial wastewater was treated, half failed to meet government standards. For regulated industries, wastewater volumes may be leveling off. However, pollution continues unabated from about 7 million small village businesses, which release largely untreated wastewater. China has shut down many thousands of the worst of these, but even as it did so, water pollution from agriculture and domestic water use was increasing. Farmers use inappropriately large amounts of pesticides and fertilizers, much of which runs off into surface water or seeps into groundwater.

A World Resources Institute report indicates that in 1995, China had only 100 modern municipal wastewater-treatment plants. These treated only 1 billion of the 30 billion tons (0.9 billion of the 27 billion tonnes) of urban sewage produced. Not surprisingly, about 700 million of China’s 1.3 billion people drink water that does not meet health-based standards for microorganisms, industrial chemicals, or nitrate (from nitrogen fertilizer). High incidences of human diseases are reported along some of China’s rivers. Moreover, farmers continue the historical practice of using human sewage on their crops. They now also use irrigation water containing high levels of industrial chemicals, such as lead and chromium, leading to high metal levels in some crops. China also continues to build large dams, which may exacerbate water pollution. One of these dams, the Three Gorges Dam being built along the Yangtze, will be the largest in the world.

In a different context, tropical dam reservoirs are associated with high levels of mercury contamination in fish, growth of cyanobacteria (blue-green algae which often produce toxins), and poor-quality drinking water. The reservoirs also lead to epidemics of vector-borne diseases such as mosquito-borne malaria.

Reducing pollution in China

One author recently wrote an article with the optimistic title, China: the next environmental superpower? Indeed China’s State Environmental Protection Administration (SEPA) believes that, although environmental quality is still “grave,” it is stabilizing. SEPA reported that pollutant discharges in 2001 were roughly the same as in 2000. However, SEPA also reports facts such as the following. In 2000, 23.4 billion tons (21.3 billion tonnes) of sewage and industrial waste were discharged into one major river, the Yangtze and its branches, an amount 11% greater than in 1999. Nonetheless, an environmental infrastructure is being built. The World Bank believes that although China needs to spend much more on the environment, its environment can recover and even become sustainable. Zhu Jianqiu, a SEPA official pledged a dedicated fight against pollution, with water pollution as one of the top priorities. China is constructing more water-treatment plants, and has subjected industrial effluents to taxes and permits. However, millions of small village-based businesses remain unregulated. A related problem is that it is the provincial governments that have the responsibility of enforcing the central government's Water Pollution Control and Prevention Law, and it is they who are expected to improve water quality. However, these officials fear "political suicide" if environmental improvements affect economic growth. This is true "even in the face of impending crisis." According to Changhua Wu of the World Resources Institute, "economic growth is the number-one goal of the country, while environmental protection failed to be integrated in the decision-making process." Wu also believes that China needs more aggressive environmental policies, less end-of-pipe control, and more pollution prevention. It needs to analyze the life cycles of its industrial products and begin, on the basis of the results, to emphasize cleaner production.

SECTION VI

The "nitrogen glut"

The "nitrogen glut" is described as "one of the world's biggest environmental headaches." You are familiar now with the potential of global warming, caused by increases in atmospheric carbon levels to wreak havoc. You also understand the adverse effects of acid deposition with its ability to increase environmental levels of sulfur and nitrogen (reactive nitrogen). Actually, acid deposition contributes to the nitrogen glut although the biggest source of reactive nitrogen is runoff. Humans have doubled the rate at which reactive nitrogen is reaching plant life. Does this matter? Remember the adage, "the dose makes the poison."

Background of the nitrogen glut

Atmospheric nitrogen is biologically inert to most living organisms. Until the twentieth century, people fertilized their crops by applying manure or compost (decaying leaves, grass, and other organic materials). Or they periodically planted their fields with legumes; these have root nodules that contain nitrogen-fixing bacteria, and so boost reactive nitrogen in the soil. The problem of limited amounts of reactive nitrogen in soil, and therefore of limited crop growth was solved in 1913 by the development of the Haber–Bosch process. With the input of much energy, this process fixed atmospheric nitrogen into ammonia. Ammonia can be used directly as a fertilizer or converted into nitrate used in fertilizer mixtures that also commonly contain phosphorus and potassium. Synthetic fertilizer has received credit for allowing humanity to increase food production to keep pace with population increases in the twentieth century. Over half of all synthetic fertilizer used in human history was used in the last 20 years of the twentieth century. The amount of synthetic fertilizer now used each year has come to equal the amount of naturally available reactive nitrogen, and its use is growing.

Nutrient sources

Runoff of fertilizer nitrate applied to agricultural fields and, to a lesser extent, to yards and greens is the major source of excess reactive nitrogen reaching rivers, streams, lakes, and coastal areas. Fertilizer use is projected to increase about 70% by 2020. This is especially so in Asian, African, and South American countries, which now use relatively little. The amount of nitrate reaching coastal areas is directly related to the amount that runs off, so as fertilizer use increases, the amount of nitrate that rivers carry into coastal zones could more than double by 2050 compared with 1990 levels. With effort and expense, much nitrate can be trapped by grass and tree buffer zones or by wetlands before it reaches waterways (Table 9.1). *Burning fossil fuels* is a secondary, but important, source of reactive nitrogen. Nitrogen oxide (NO_x) emissions worldwide quintupled in the twentieth century so that NO_x now represents about one-quarter of the reactive nitrogen that humans produce. As with fertilizer nitrate coming from far upriver, atmospheric nitrate can also come from afar. However, unlike reactive nitrogen from fertilizer, NO_x cannot be trapped in buffer zones: it is deposited directly from the atmosphere after conversion to nitrate or nitric acid. Poorly treated or untreated *sewage* is a nutrient source too; so is runoff of animal manure. Any *organic matter* has nutrient value, so any excess amount of such matter reaching water bodies contributes to reactive nitrogen increases in water. *Natural sources* of reactive nitrogen also exist. Bacteria produce the largest natural amount; of most interest here is reactive nitrogen produced by bacteria in the root nodules of certain plants, especially legumes. A small amount is also produced during lightning.

Figure 9.6 summarizes reactive (fixed) nitrogen sources and how their output has continued to grow over the years. ■ Note (second curve from top) that total reactive nitrogen in the environment began growing in the early twentieth century, but grew much more rapidly later in this century. ■ The third curve from the top, Haber–Bosch nitrogen, explains much of this growth as more and more synthetic fertilizer is used to promote crop and grass growth. ■ But, see in the fourth curve, Nitrogen fixed by crops (especially legumes) that this source has been growing too as human agricultural activities have

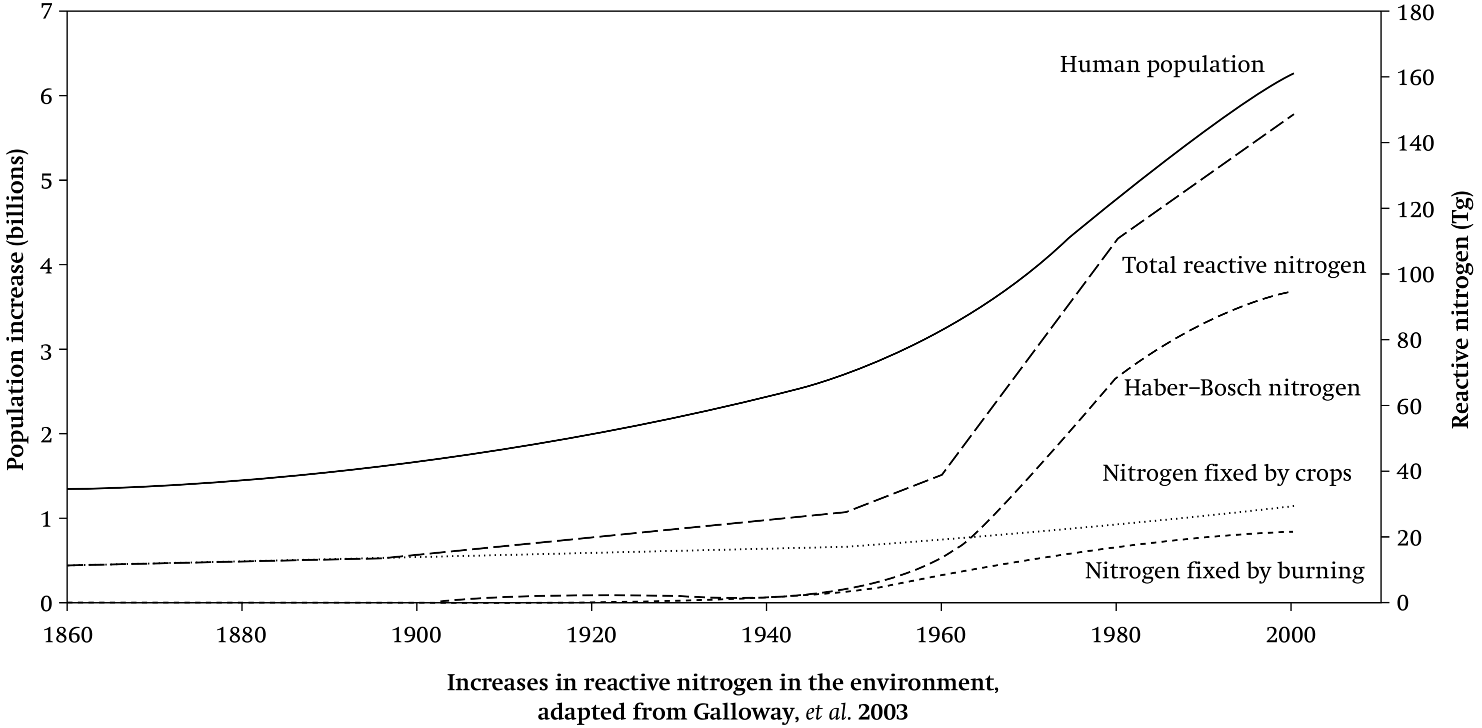

Figure 9.6 Increases in reactive nitrogen in the environment. Units for reactive nitrogen are teragrams (Tg; 1 Tg is 1 trillion grams). Credit: Galloway, J. N., Aber, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. H., Cowling, E. B., and Cosby, B. J. The nitrogen cascade. *Bioscience*, **53**(4), 2003, 341–356

grown. ■ See too, Nitrogen fixed by burning (curve 5); as we burn more and more fossil fuels we fix more and more nitrogen too. ■ Finally, go to the top line – Human population. Notice how as population grows, so does the output of reactive nitrogen.

Adverse effects of excess nutrients

Reactive nitrogen is already a critical problem in some places, and is fast becoming a planet-wide problem. Excess nutrients change the composition of life forms starting at the bottom of the food chain. This change moves through the food web to affect plant, bird, and animal diversity. Excess reactive nitrogen can also result in algal blooms and "dead zones" (described below). Reactive nitrogen is emphasized here, but phosphorus can also cause major harm, especially in freshwater bodies.

Livestock operations

Reactive nitrogen in manure is much less concentrated than in synthetic fertilizer but – because of their often great size – runoff of waste from confined-animal feeding operations (CAFOs) can be a major nutrient source. At any one time, the United States has 60 million pigs, 47 million beef and dairy cows, and 7.5 billion chickens. Typically kept in confinement, they produce about a billion tons of manure and urine a year, which is often stored in lagoons. In a 1995 incident in North Carolina, a lagoon leaked 25 million gallons (113 million litres) of hog waste into the New River, leading to an algal bloom with resultant oxygen depletion, and killing fish and other aquatic organisms. Other ways that CAFOs can pollute is through chronic seepage from animal-waste lagoons and runoff from fields onto which the lagoon liquids are sprayed. Both surface-water and groundwater contamination occurs. In Colorado towns near large beef-cattle feedlots, groundwater nitrate concentrations are double the EPA human-health standard. Livestock operations also generate the pungent gas, ammonia. Rained out, this is converted to nitrate in the soil, contributing to acidification. In North Carolina, ammonia in rain increased 25% between 1990 and 1995, coincident with increased pig production. ■ The Netherlands has intensive pig farms too. Although a very small country, it produces almost one-quarter as much pork as does the United States and it has similar problems. However, its government places the most stringent controls in the world on these operations; it has mandated a 25% reduction in the pig population, and has a system to account for all the nutrients entering or leaving its borders. These actions reduce, but do not eliminate, escaping nutrients. Sadly, probably as a result of this careful regulation, intensive-pig-farm owners are now setting up in the United States where regulations are more lenient. ■ Worse still is the setting up of these industrial-size livestock operations in less-developed countries that are especially ill-equipped to handle the resulting pollution.

Algal blooms

Excess nitrate and phosphorus from fertilizers, atmospheric deposition of nitrate, plus nutrients in sewage and manure are associated with eutrophication. In coastal areas nitrate is the major culprit whereas in fresh water lakes, it is more often phosphorus. ■ Any algal bloom can have ill-effects: by crowding out the growth of other plants and covering the water surface so thickly that sunlight is prevented from reaching underwater grasses. These grasses provide food, shelter, and a spawning ground for crabs, fish, and other aquatic creatures as well as habitat for their offspring, and food for water fowl. ■ A bloom can create aesthetic problems too, i.e., scum and unpleasant smells. A bloom also exerts BOD as it is degraded by oxygen-requiring bacteria, sometimes leaving the water hypoxic. ■ *Harmful algal blooms* (HABs), in addition to the problems just noted, also produce toxins. The bloom of one dinoflagellate, *Gonyamlax*, appears as a red tide in marine coastal water. Red-tide organisms produce a toxin that accumulates in the fish and shellfish that eat them. The fish may become ill and suffer impaired reproduction and damaged immune systems. Humans eating the contaminated shellfish may suffer from paralytic shellfish poisoning. The occurrence of a red tide is one reason for placing a ban on eating shellfish in an affected area. Water birds and other sea life may also suffer ill-effects. The diatom *Pseudo-nitzchia australis* can also generate a noxious HAB producing the neurotoxin *domoic acid*. In a 1987 case, 140 people in Canada's Prince Edward Island were poisoned after eating mussels that had eaten this diatom. Three died, and others suffered memory loss that was still apparent in 2000. In California, the 1998 deaths of 400 sea-lions was convincingly tied to their eating of anchovies that had eaten the domoic acid-producing algae. Other algal toxins have been associated with a variety of other ill-effects including tumors in sea animals such as turtles.

Dead zones

A water body or a portion of a water body where oxygen has been depleted is called a dead zone. Several examples of dead zones follow.

The *Black Sea* is an almost landlocked body of water in Eastern Europe bordered by Bulgaria, the Republic of Georgia, Romania, Russia, Turkey, and Ukraine. Activities in these and 15 other countries upstream on the Danube River, badly polluted the Black Sea with fertilizers, untreated human sewage, and industrial waste. Year-round severe eutrophication and hypoxia developed, and the incidence of red-tide blooms greatly increased. A final blow came in the early 1980s when an exotic (foreign) species, the Atlantic jelly comb was accidentally released into the Black Sea. This jelly fish bloomed so ferociously that it became the dominant Black Sea species. It destroyed native fish species, and 20 of the 26 commercial fish species became extinct. Finally, the jelly fish almost wiped out the zooplankton on which they themselves fed, leading to the collapse of their own population. Countries bordering the Black Sea finally developed a plan to reduce nutrient inputs and encourage treatment of human sewage. A major change occurred after 1990. The Soviet Union had supported agriculture including chemical fertilizer use. After its government collapsed, fertilizer use fell by more than half. In 1996, after more than 30 years, the dead zone disappeared. As economic conditions improve, fertilizer use will doubtless again increase. Unless regulated by governments – by, for example, requiring buffer zones around agricultural fields to absorb agricultural runoff – the dead zone could again appear.

Beginning in the late 1970s, *Denmark's Kattegat Strait*, which links the North and Baltic Seas suffered algal blooms, low-oxygen water, and fish kills. A lobster die off in 1986 finally focused attention on the problem. A plan was developed to cut nutrient input to the strait, phosphorus by 80% and nitrate by 50%. Farmers were to limit application of fertilizer and manure to their fields. When, by 1998 nitrate inputs still had not decreased, the government bought land from farmers to establish wetlands and forests to soak up nitrate, and also paid farmers to use less fertilizer.

The phosphorus effort was more successful. Industry and wastewater-treatment plants successfully reduced phosphorus in their effluents, and over a 14-year period the desired 80% reduction in phosphorus was achieved. Because algal blooms in part of the affected coastal area are limited by the amount of phosphorus available, conditions improved with, e.g., oxygen levels rising in the strait's open waters.

In the US *Gulf of Mexico*, a dead zone – which at its largest was equivalent in size to the state of New Jersey – occurs each summer in bottom waters near the mouths of the Mississippi and Atchafalaya Rivers. The Gulf of Mexico drains water from 31 states, representing about two-thirds of the water of the continental United States, starting in Minnesota and including every state between the Rocky and the Appalachian Mountains. The gulf receives massive doses of nutrients. An estimated 16% of all nitrate fertilizer applied to crops in the Mississippi River watershed runs off and is delivered to the gulf. This reactive nitrogen is estimated to account for two-thirds of the nutrient problem. Additional nutrient inputs come from runoff of manure at confined-animal feeding operations and point-source pollution from municipal wastewater-treatment plants. Studies of gulf sediment showed that nitrate levels had increased three-fold since 1960 and phosphorus two-fold. The excessive nutrients stimulate algal blooms in the gulf leading to hypoxic water. As oxygen becomes increasingly scarce, fish move elsewhere. Other creatures, including crabs and brittle stars, are unable to move and suffocate. This dead zone is in a region that provides 40% of US seafood. If it worsens, it could impact upon the food supply. A 31-state plan has developed proposing to pay farmers to reduce fertilizer use, restore wetlands, plant tree or grass buffers between crops and streams, reduce manure runoff, and assist municipal sewage-treatment plants to upgrade their equipment enabling them to remove more nitrate and phosphorus. However, even if the plan works, nitrogen input to the gulf will decrease only 30%, a partial solution. Nonetheless, because a major conflict exists between farmers, fishermen, and environmentalists, the plan is considered "real progress." In Denmark, "the farmer lives next to the fisherman," and they must get along. In the United States, these groups, separated from one another geographically, have difficulty seeing each other's perspectives. ■ Other dead zones are found in the Adriatic Sea, the US Chesapeake Bay, Hong Kong Harbor, and Japan's Seto Inland Sea.

Other environmental risks of reactive nitrogen

This section has described the adverse effects of excess reactive nitrogen in surface water, including hypoxia and eutrophication; it has also described the adverse health effects of nitrate in groundwater. But remember reactive-nitrogen has other effects: ■ NO_x is a major contributor to ground-level ozone. ■ NO_x is a major contributor to acid deposition. ■ Increased reactive-nitrogen pollution can cause reduced biodiversity in water bodies.[12]

Reducing the nitrogen glut

■ Some methods of reducing runoff of fertilizer and manure into water are summarized in Table 9.1, but implementing these can be difficult. Farmers feel they will get a lower yield if they use less fertilizer, and it also takes resources to set up buffer zones. Thus, farmers don't usually act voluntarily. And owners of confined-animal feeding operations often fight attempts to require them to change how they handle animal waste. Even with cooperation, the task is difficult. ■ People eating less meat would reduce the problem: an animal eats several pounds of grain per pound of meat produced. Thus more grain is grown – and more fertilizer used – than if humans eat grain directly. And animals release reactive nitrogen in their wastes. As income increases in some parts of the world, more people eat more meat. About 40% of the world's grain is currently used to feed food animals. ■ Another approach to reducing nitrogen in manure is to feed food animals a diet that results in less reactive-nitrogen excretion; that too is expensive.

As shown in the section on dead zones, it *is* possible to solve these difficult problems. Although fertilizer use in poorer countries is increasing, new methods may minimize its problems while still maintaining high production: ■ The UN Food and Agriculture Agency has a simple machine to implant fertilizer cakes deep in the soil. This much reduces fertilizer runoff. ■ Methods exist too that reduce the NO_x emitted by power plants. Moreover, NO_x emissions could be trapped and converted into fertilizer, but this is costly compared with using

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[12] In water, excess reactive nitrogen disproportionately stimulates the growth of certain algae relative to other species. On land too, reactive-nitrogen pollution can lead to fewer species. Those species whose growth is most stimulated crowd out other species. In a 12-year study, researchers grew a variety of grasses in plots with differing amounts of nitrogen fertilizer. The fertilizer stimulated the growth of some grass species more than others. Plots with higher amounts of fertilizer had a different species composition than did those with little fertilizer.

traditional synthetic fertilizer. Although producing reactive nitrogen from atmospheric nitrogen is energy intensive, energy is still relatively cheap. ■ On a more positive note, Europe expects to reduce NO_x emissions by more than 40% by 2010 as a result of a 1999 treaty, the Gothenburg Protocol. ■ In the United States, NO_x emissions and fertilizer runoff are still poorly controlled. One observer commented pessimistically, "Our population is growing, vehicle miles driven are increasing . . . , and we are changing our land-use patterns and deforesting the landscape. We are not making the lifestyle changes needed to cap nitrogen inputs." Moreover, sources of reactive nitrogen are often far from the coastal areas where the environmental impact occurs, and people balk at taking responsibility for distant adverse effects.

Some observers hope that more research will provide additional possible solutions. Experts believe that the major problem is perhaps ". . . people haven't recognized the global nature of nitrogen and that human activity is altering the nitrogen cycle." That recognition may be slowly occurring. United Nations' studies project that reactive nitrogen will soon be a global problem. The US National Research Council has urged the government to develop a strategy to combat both nitrogen and phosphorus pollution.

Questions 9.3

1. Review the term natural (or ecosystem) services (Chapter 1). What natural services did wetlands and forests supply in Denmark that led to reduced fertilizer input to the Kattegat Strait?

2. (a) Show diagramatically how releasing organic matter (with BOD) to a water body has some of the same effects as excess nutrients. (b) Why is the nitrate and phosphate in synthetic fertilizer more effective at stimulating an algal bloom than that in organic matter?

3. Dr. Stephen Eisenreich of Rutgers University believes that eutrophication is probably the major water-quality problem that the United States faces. He commented that although environmental health is critical to ongoing economic development, Americans seem willing to accept eutrophication and the other adverse impacts of urban sprawl rather than change their land-use practices. See an example of this resistance in Chesapeake Bay (Box 9.6). (a) How does urban sprawl increase nutrient input to plant life? (b) Lay out a strategy that you believe may be fairly successful in reducing eutrophication in an area affected by eutrophication.

4. (a) How does excess nutrient input to a water body result in changes in the composition of plant life found there? (b) How can a change in plant species affect aquatic life?

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Chapter 10

Drinking-water pollution

The "wall between us and microbes, is beginning to crumble."

American Academy of Microbiology

Most of us in developed countries take clean and plentiful water as a given, not just drinking water, but water for many household, yard, and other uses. Yet, says the American Academy of Microbiology, "Microbiologically safe drinking water can no longer be assumed, even in the United States and other developed countries, and the situation will worsen unless measures are taken in the immediate future – the crisis is global." Treating drinking water to kill pathogens is given much credit for increasing the life span of US citizens, from 47 years at the turn of the twentieth century to 77 years. But the twenty-first century begins with one-fifth of the world's humanity still without clean drinking water. Even poor-quality water is becoming scarcer because ever-increasing numbers of people live in areas of water scarcity in which not only is drinking water a problem, but also water for sanitary needs. Within 10 to 15 years the United Nations estimates that at least 40% of the world's people will live in countries where they cannot get enough water to satisfy basic needs. Wildlife is increasingly deprived of water. Domestic animals may go wanting too. Demand for fresh water increased six-fold in the twentieth century, more than twice the rate of population growth. Reasons for water scarcity include increasing human populations that need and want ever-more water. Industrial use of water has increased too. However, most of the increased water use has arisen from irrigating farmland.[1]

Less than 3% of the water on Earth is fresh water. Only about one-third of this is available for human – and wildlife – use. The other 2% is frozen into polar ice sheets and glaciers. ■ The remaining 97%

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[1] Competition over water resources could lead to violent international conflict. "A looming crisis that overshadows nearly two-thirds of the Earth's population is drawing closer because of continued human mismanagement of water, population growth, and changing weather patterns." UN Secretary Kofi Annan speaking on World Water Day (22 March, 2002).

of Earth's water, including that in the Earth's oceans is too salty to drink. ■ Brackish water is less salty than ocean water, but not potable. Some groundwater is also too brackish to drink as is certain surface water such as that in Utah's Great Salt Lake. Another reason for a drinking-water scarcity is that an increasing amount of fresh water is too polluted to drink.

Section I addresses drinking-water protection in developed countries, with an emphasis on the United States. Common drinking-water contaminants are examined along with the primary and secondary standards set to reduce them. Drinking-water treatment and disinfection are surveyed too. **Section II** describes the often critical contamination of drinking water, especially pollution with pathogenic agents seen in less-developed countries. Another drinking-water contaminant, arsenic, has also resulted in mass poisoning.

SECTION I

Developed countries

Drinking-water standards

Human activities that pollute drinking water were seen in Chapter 9. Drinking water in the United States is regulated under the Safe Drinking Water Act (SDWA) first passed in 1974. This law sets national health-based standards for microorganisms and toxic substances. Standards are enforceable by law to ensure uniform health standards nationwide. Surface water is more likely to be significantly contaminated, but contaminated groundwater is an increasing concern. Some contaminants such as taste, odor, and color, are primarily aesthetic concerns. Others, those for which primary standards exist, are human-health risks. In the early twentieth century, communities began treating their drinking-water supplies. The primary purpose of treatment is to destroy pathogens. Over the years, treatment evolved to also include clarifying water and removing components contributing to unpleasant taste, odor, or water hardness (Figure 10.1).[2]

Box 10.1 | Is fluoride a pollutant?

Fluoride is added to drinking water in about half of US communities to lower the incidence of tooth decay among children. After more than 50 years of use, fluoridation remains controversial because some believe it is harmful to health. Critics also assert that lax monitoring leads to fluoride levels that, in some cases, are high enough to harm human health. As one example of this, a baby grape juice was found to contain 6.8 ppm fluoride. This is 70% higher than the EPA's maximum

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[2] *Hard water* contains dissolved mineral salts, such as calcium and magnesium carbonates, that prevent soap from sudsing or that cause deposits on pipes and in appliances in which it is used.

contaminant level (MCL) for fluoride of 4 mg/l (4 ppm) in drinking water. In turn, the MCL itself is higher than the 0.7 to 1.2 mg/l considered optimal to prevent caries. People ingest yet more fluoride from food and beverages processed with fluoridated water. Fluoride is also sometimes found in toothpaste, which children may swallow. Fluoride is also found naturally in water, usually at low levels, but sometimes at higher concentrations than the level useful to prevent tooth decay.

In a few people who ingest more than 2 mg/l, stained or pitted teeth develop over time. Moreover, a few cases are known of people who, for many years drank water that naturally contained more than 8 mg/l fluoride; as a result some developed crippling skeletal disease. A 1994 US Centers for Disease Control and Prevention (CDC) report stated that fluoride, at typical exposure levels, does not cause bone disease, cancer, infertility, birth defects, or other ills sometimes attributed to it. Although the CDC gave its support, it noted that water fluoridation should be carefully used, and that more research was needed. Meanwhile, European countries, which don't add fluoride to water, express concerns about even natural fluoride levels.

Primary drinking-water standards

Most pollutants of concern in drinking water are typically found only at low levels. Thus, the primary concern is potential chronic health effects that might result over years of drinking the water. Potential

Figure 10.1 Drinking-water treatment process

DRINKING-WATER SOURCE
⇓
SCREENING
The purpose of screening is to remove debris. Suspended particles remain in the water.
⇓
COAGULATION THEN FLOCCULATION
Chemicals are added to coagulate suspended particles. Then, water is agitated so coagulated material forms a floc.
If not removed, suspended particles can affect taste and color, or interfere with water disinfection.
⇓
SEDIMENTATION
The floc settles from the water over about a day's time.
⇓
FILTRATION
This removes the solids remaining in the water, and removes many but not all microorganisms.
⇓
DISINFECTION
Disinfection is used to kill remaining microbes. In the United States the disinfectant is often a chlorine-containing chemical. In Europe it is often ozone. Because ozone dissociates into oxygen, another disinfectant is needed to maintain disinfection as water is transported to consumers. Historically the beginning of water disinfection marked the end of typhoid and cholera epidemics.
⇓
OTHER STEPS
The water may be aerated to remove volatile organic chemicals and radon.
Yet other steps may be added to remove pollutants present at above health-based standards.
⇓
DISTRIBUTION
Drinking water is transported through pipes to individual consumers.

Table 10.1 Primary drinking-water standards (examples)

Contaminant	MCLG (mg/l)	MCL (mg/l)	Sources of contaminant
Volatile organic chemicals			
Benzene	0	0.005	Some foods, gas, drugs, pesticides, paint
Carbon tetrachloride	0	0.005	Solvents and their degradation products
p-Dichlorobenzene	0.075	0.075	Room and water deodorants, mothballs
Other organic chemicals			
Atrazine	0.003	0.003	Runoff from use as herbicide
Chlordane	0	0.002	Leaching from soil treatment for termites
Chlorobenzene	0.1	0.1	Waste solvent from metal degreasing
PCBs	0	0.0005	Coolant oil from electrical transformers
Benzo[*a*]pyrene	0	0.0002	Coal-tar coatings, burning organic matter
Inorganic chemicals			
Barium	2	2	Natural deposits, pigments, epoxy sealants
Cadmium	0.005	0.005	Galvanized pipes, natural deposits, batteries
Nickel	0.1	0.1	Metal alloys, electroplating, batteries
Nitrate	1	1	Animal waste, fertilizer, natural deposits

The above pollutants are examples of those for which the US EPA sets primary standards. The complete list is at http://www.epa.gov/OGWDW/mcl.html.

chronic effects are the reason why metals such as lead and cadmium, organic pollutants such as solvents, and pesticides are regulated. Pesticides, except where spills have occurred, are not normally found in drinking water at levels that can be acutely toxic – again the major concern is: Could there be chronic effects? The EPA sets *primary standards* for many of the pollutant types just mentioned. Setting standards involves two steps. (1) It determines a *maximum contaminant level goal* (MCLG), a level not expected to cause adverse health effects even over a lifetime of exposure. (2) Because achieving the MCLG is not always possible, the EPA also sets an achievable *maximum contaminant level* (MCL). The MCL is set as close to the MCLG as possible. The MCL is an enforceable standard. MCLs have been set for nearly 100 pollutants (Table 10.1). If a chemical is detected in water at a concentration greater than its MCL, its level must be reduced using *best available technology*. Absorption using activated carbon is commonly used to reduce the levels of a number of pollutants. Some drinking-water contaminants are natural. These include arsenic and the radioactive elements radon and radium. If natural sources of regulated substances exist, the EPA takes natural levels into account when setting standards.

Two pollutants posing immediate threats

The purpose of most primary standards is to guard against potential chronic health effects. However, two contaminants – nitrate and bacteria – pose an immediate threat to health or life if primary standards are exceeded.

Microorganisms

Destroying pathogenic agents remains the primary reason for treating drinking water. Bacteria are naturally present in water. However, fecal coliform bacteria in the water may indicate human or animal wastes because these bacteria inhabit the intestines of humans and other vertebrates. Coliform do not necessarily cause disease themselves. Rather they are an indicator of fecal material, which may contain pathogens. Coliform are used as an indicator because simple inexpensive methods are available to detect them. If coliform are found in the water, then it is tested further for the presence of organisms definitely known to be pathogens. Enteric viruses are pathogens which can cause gastrointestinal distress. *Legionella* bacteria are responsible for the respiratory disease, Legionnaire's disease. *Giardia lamblia*, a protozoan, causes intestinal illness. Any of these diseases can be serious or, sometimes, deadly.

Sources of pathogens include poorly maintained sewage-treatment systems, malfunctioning septic systems, runoff of animal manure, and other storm-water runoff. Pathogenic agents can also come from fish, water birds, and wild animals. Before the twentieth century, drinking water contaminated with pathogens frequently caused epidemics of cholera, typhoid fever, amebic dysentery, and other diseases. Small children, especially, often died from waterborne diseases and still do in less-developed countries. As communities began disinfecting drinking water in the early twentieth century, these diseases fell dramatically in developed countries. Nonetheless, pathogen contamination did not disappear. A 1985 US CDC report estimated that 940 000 Americans become ill each year from infectious organisms in drinking water, and about 900 die. Other recent estimates are considerably higher. People at greatest risk are infants, elderly people, and individuals whose immune systems are compromised by other illnesses. An especially serious incident occurred in the United States in 1993 when about 400 000 people in Milwaukee, Wisconsin became ill after drinking water contaminated with the parasitic protozoan, *Cryptosporidium* and more than 100 died.

Nitrate

The second contaminant posing an immediate threat to health is nitrate, a nutrient found in fertilizer, manure, and sewage, and formed in the atmosphere from nitrogen oxides. Nitrate is most often found at high levels in the groundwater of agricultural areas where it infiltrates wells after fertilizer use, or from manure due to animal operations nearby. Infants are most vulnerable because nitrate is converted to *nitrite* in infant stomachs more readily than in adults or older children. After nitrite is absorbed into the bloodstream, it reacts with the iron in the infant's hemoglobin to produce *methemoglobin*, which cannot carry oxygen. The result may be "blue-baby" syndrome. Excessive nitrate ingestion has resulted in infant deaths in the mid-western United States.

Disinfection byproducts

Disinfection is vital to most drinking water. Unfortunately it can result in contaminants too. Chlorine disinfection of water forms a variety of disinfection byproducts (DBPs). DBPs result from the reaction of organic material in the water with chlorine. Higher chlorine concentrations produce higher levels of DBPs, especially if significant quantities of organic material are present. ■ *Chloroform* is the DBP produced in the largest amount. At high doses, this chemical is an animal carcinogen. The US EPA has established an MCL for total *trihalomethanes*, a family of DBPs found in chlorinated water; that is, trihalomethanes are a primary water pollutant. Epidemiological studies suggest that drinking chlorinated water for many years increases the risk of bladder and rectal cancer. This raises a dilemma because disinfection is critical for killing harmful microorganisms, and disinfectant levels must be high enough to accomplish this. Some argue that chloroform levels, and total DBPs more generally, are not of concern, especially balanced against the risk of infectious diseases. ■ Methods exist to remove DBPs from drinking water, but this is a costly end-of-pipe process. Another approach is to remove as much organic material as possible from water before chlorinating it. This results in lower levels of DBPs.

Alternative disinfectants produce smaller amounts of DBPs. However, to varying extents, all disinfectants form DBPs. The alternative disinfectants are incompletely characterized and may also pose health problems. What are these alternative disinfectants? ■ *Chlorine dioxide* effectively disinfects water while producing much smaller quantities of DBPs. An increasing number of US communities use chlorine dioxide. The chemical *chloramine* is effective too, and produces fewer DBPs. ■ *Ozone* disinfection works better than chlorine even, but cannot maintain disinfection as it decomposes into oxygen. So a small amount of chlorine must be added before piping the water to users. This forms DBPs, but much smaller amounts. Many consider ozone the ideal disinfectant. However, the ozone DBP, *bromate*, is a strong animal carcinogen for which the EPA has established an MCL. Ozone disinfection is more expensive too, and needs more highly trained operators. ■ Exposing water to ultraviolet light can kill pathogens, but this has been expensive and used primarily to treat small volumes of water. As with ozone, small amounts of a chemical disinfectant must be added to UV-disinfected water before piping it to users. Inexpensive versions of UV light disinfection are being explored for use in impoverished countries. ■ Distilling water can purify it and the distillate has no DBPs. However distillation is usually costly and the distilled water lacks minerals, and lacks taste as well.

Disinfection is critical when water is impure. But if a community conscientiously works to reduce infectious microorganisms in its water supply, that water needs less or no disinfection. Recall that New York City is using pollution prevention (P^2), spending money to buy and protect land bordering the water bodies that supply its water. The US EPA and a number of states have watershed-protection programs to maintain the purity of water sources. ■ Individuals too, those with private wells, can make sure there is no source of pathogens that can reach the groundwater that serves the well. See Table 9.1 for approaches used to reduce polluted runoff. As population continues to increase and development pressures grow, maintaining water purity becomes more important even as it becomes more difficult.

Questions 10.1

1. Many individuals obtain drinking water from wells. (a) To avoid pathogen contamination of a well, where should they locate it? (b) To avoid contaminating the well with fertilizer or pesticides, where should it be located? (c) What other contaminants might get into a well in the area where you live, and how can the contamination be prevented? (d) How might the well's age affect the risk of groundwater contamination? Explain.
2. Think about a community that obtains its drinking water from a well. What are practical steps that it can take to educate its citizens to protect the source of their water?

Maintaining drinking-water standards

In Europe, lead, pesticides, and nitrate runoff from agricultural lands and livestock operations are water pollutants of special concern. Europeans also express concern that exposure to and health effects of water pollutants have not been properly assessed. In the United States, the EPA requires states to evaluate the performance of their water-supply systems, but many fail to do so due to limited resources. Many water-treatment systems are aging, or lack the modern technology needed for optimal performance. Most US public water systems are small, serving 25 to 3300 customers. At one time, small systems had only to meet standards for water clarity, bacteria, and nitrate levels. After 1986 they were required to meet the more-demanding regulations of larger systems. Nonetheless, in 2000, the cost of drinking water to US citizens was low, an average of $0.51/m^3 as compared to $1.15/m^3 in the United Kingdom and $1.82/m^3 in Germany.

Secondary drinking-water standards

Secondary standards are designed to protect "public welfare" (Table 10.2). They are guidelines for substances that affect the water's aesthetic qualities, such as taste, odor, and color, but that do not pose a health risk. They are unenforceable unless individual states treat them as enforceable.

Other issues

- Increasing population densities. High population densities already exist in a number of European countries. The United States is still land rich, but with its population growing at 1% per year, some locales are becoming increasingly crowded, which makes it more difficult to maintain pure drinking-water sources.

Table 10.2 Secondary drinking-water standards

Contaminant	Suggested levels	Contaminant effects
Aluminum	0.05–0.2 mg/l	Discoloration of water
Chloride	250 mg/l	Salty taste and corrosion of pipes
Color	15 Color units	Visible tint
Manganese	0.05 mg/l	Taste or staining of laundry
Sulfate	250 mg/l	Salty taste, laxative effects
Total dissolved solids	500 mg/l	Bad taste, may damage plumbing, or limit effectiveness of detergents
Odor	Threshold odor	Rotten egg, musty, or chemical smell
pH	6.5–8.5	Low pH: bitter metallic taste, corrosion High pH: slippery feel, soda taste, deposits

- Sensitive groups. The United States and other industrialized countries have begun to evaluate what to do about specific populations that are especially sensitive to contaminants, including the aged with deteriorated immune systems, and infants and small children whose immune systems are immature. Others have immune systems impaired by AIDS, cancer, radiation therapy, organ transplants, or serious chronic diseases. These persons may be advised to boil drinking water or to drink bottled water to avoid microorganisms that may have survived in tap water. Another group of people routinely advised to drink bottled water is those who travel to poor countries where microbes may exist in tap water (Box 10.2).
- Emerging problems. In the 1990s, several infectious-disease outbreaks were traced to drinking water in North America. The worst by far was an outbreak of *cryptosporidiosis* in Milwaukee, Wisconsin. It affected 400 000 people and over 100, those who were already ill, died. Another cryptosporidiosis outbreak in Walkerton, Ontario (Canada) affected 13 000. In response to such problems, the US EPA began to focus more strongly on ambient-water-quality criteria, and will establish pathogen monitoring protocols, guidelines for septic-system operations, and requirements for water-reuse applications. The EPA is also developing a risk-assessment protocol for waterborne infectious diseases, as well as examining pathogens in sediments.

Box 10.2 Bottled drinking water

Sales of bottled water in the United States increased nine-fold in the last 20 years. People believe that bottled water is purer than tap water, or prefer its taste. The Natural Resources Defense Council a US environmental organization had 103 brands tested. Results revealed that about one-quarter of the brands were simply tap water, although some had been further treated. About one-third of the brands had contaminant levels exceeding those allowed by state or bottled-water industry standards, but most appeared safe and clean. Similar situations are reported elsewhere: ■ A University of Geneva, Switzerland study found that a bottled-water category called "purified" was drawn from rivers, lakes or underground springs and treated. Its quality was usually good, but some samples had the same contaminants as, and generally differed little from, tap water. ■ Similarly, a University of Winnipeg, Canada study examined 40 domestic and imported bottled-water brands. It found some brands in which total dissolved solids, chloride, and lead exceeded the Canadian Water Quality Guidelines for drinking water. ■ In all three countries, bottled water is much more expensive than tap water. Over industry objections, the US Food and Drug Administration recently proposed that bottled water should have labels providing the same contaminant information that drinking-water utilities must provide once a year to their customers.

SECTION II

A global crisis

Pathogen contamination of drinking water is already critical in many less-developed countries. Upon hearing the term "water pollution," chemical pollution may first come to mind. Yet the major problem of more than one billion people in impoverished countries is typically pathogen-contaminated drinking water. This is not surprising considering that close to 2.5 billion people lack access to proper sanitary facilities. Thus, there are pathogens in their water, their food, and their environment more generally. Whole villages in some locales, especially their children, suffer debilitation from chronic waterborne infections.

If industries are also present, often releasing poorly or untreated effluents, or if there is agricultural runoff containing pesticides and fertilizers, then chemical pollutants add heavily to the burden posed by pathogens. Aggravating the problem further is the fact that there is too little water in many locales. Box 1.2 describes conditions in one impoverished city. In an *Atlantic Monthly* article,[3] author William Langewiesche describes pollution in New Delhi that "seemed apocalyptic." . . . "The streams were dead channels trickling with sewage and bright chemicals, and the air on the street barely breathable." . . . "But newcomers keep coming."

"One of the biggest threats to human health"

Water-resources expert Peter Gleick refers to water-related diseases as perhaps the greatest failure of human development. The World Health Organization (WHO) provides information that millions of people die each year in less-developed countries from drinking water contaminated with infectious microorganisms or parasites, or from insufficient water (Table 10.3). Dirty water claims 5 to 12 million lives a year depending on the definition of water-related disease. Of these millions of deaths, 80% occur in children under 5 years old, who frequently

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[3] Langewiesche, W. and Halweil, B. The Shipbreakers. *Atlantic Monthly*, **286**(2), August, 2002, 33–49.

Table 10.3 | Infectious organisms in the water supply

Organism	Diseases	Symptoms
Bacteria	Typhoid, paratyphoid, bacillary dysentery, gastroenteritis, cholera	Headache, diarrhea, abdominal cramps, fever, nausea, vomiting occurring several hours to days after ingestion; severity varies depending on organism
Viruses	Viral gastroenteritis (up to 100 types in raw sewage[a]); also polio and hepatitis A	Symptoms seen depend on the specific virus
Parasites	Diseases from protozoans including: • *Giardia lambia* and *Cryptosporidium*	Protozoa: mild to severe diarrhea, including bloody diarrhea
	Diseases from parasitic worms: • Tapeworms, roundworms, hookworms	Worms: symptoms vary depending on specific worm – abdominal pain, anemia, fatigue, weight loss

Source: National Small Flows Clearing House. Diseases commonly caused by wastewater. *Pipeline* **7**(3), Summer, 1996, 3–5.

[a] The human immunodeficiency virus is *not* spread by water.

die from the diarrhea associated with waterborne diseases. In India alone, diarrhea kills more than 500 000 small children a year. Add in the infections resulting from eating contaminated food, and living in unsanitary conditions, and pathogen exposure accounts for millions of additional deaths. Moreover, hundreds of millions of people are sickened by impure drinking water. Indeed WHO reports that, at any one time, up to half the world's people are ill due to infections resulting from contaminated drinking water.[4]

Polluted water and water scarcity

Contamination with untreated human and, sometimes animal, waste are major sources of the pathogens causing this great toll. In less-developed countries up to 98% of human waste goes into rivers and streams untreated. People lack flush toilets, sanitary latrines, and often even a pit that can be covered. "Rivers are often open stinking sewers." In China, more than half the people – about 700 million – must drink contaminated water, particularly in rural areas. In Buenos Aires, Argentina only 2% of sewage is treated. In India, less than one-third of the people even have access to basic sanitation services let alone clean drinking water. Yet cities in impoverished nations continue their rapid growth. Especially affected by a lack of sanitation services, according to the UN environmental program are 1.7 billion people living along the coasts of south Asia, the northwestern Pacific and West Africa. In addition to having an impact upon human health, the livelihood of people working in fishing and tourism is increasingly affected too. And, wildlife and their habitats suffer greatly.

Thus, an important factor in the increasing scarcity of drinking water is that the water is too polluted to drink. And drinking water

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[4] Refer back to Table 2.1. Notice that contaminated drinking water and untreated human waste are treated as major human-health threats.

is expensive: on average, the poor in less-developed countries pay 12 times more per liter of water than do people connected to municipal water supplies. Despite the cost, the water they buy is often contaminated. People are advised to boil water for 10 minutes before drinking it. However, in for example Bangladesh it would cost the poorest people 11% of their income to buy the fuel to boil water. Thus, water is often not boiled.

Reducing pathogens in drinking water

It would cost an estimated $68 billion worldwide and a 10-year effort to provide clean drinking water to all in the world who need it. This is an amount equivalent to about 1% of the amount that the world spends on military expenditures. In 1992, *Agenda 21*, that emerged from the Earth Summit in Rio de Janeiro, spelled out universal access to safe drinking water as a goal. Subsequent efforts partially succeeded in increasing access to clean drinking water. However, population growth and lack of adequate funding has left at least 1.1 billion people without clean drinking water at the beginning of the twenty-first century, and 2.4 billion lack adequate sanitary facilities.

However, at another world conference, the 2002 World Summit in Johannesburg, 10 years after Rio, the world's nations again made commitments: by 2015, they will halve the proportion of people without access to safe drinking water, and halve the proportion of people who do not have access to basic sanitation.

Questions 10.2

Latin America had been free of cholera (caused by the bacterium *Vibrio cholera*) for a hundred years. Then, in about 1991, Lima (Peru's capital city) ceased chlorinating the city's water after reading a US EPA report indicating that chlorination-disinfection byproducts could cause cancer. Later, Lima's water supply was contaminated by *Vibrio cholera*. Over the years since 1991, hundreds of thousands have become ill with cholera in Latin America and about 10 000 died. Cholera is now endemic to that region. Now, think back to the risk assessment described in Chapter 4.

1. How does the risk of disinfection byproducts differ from the risk of not disinfecting drinking water?
2. Which should be emphasized, acute or chronic health effects? Explain.

Box 10.3 Arsenic – "the largest mass poisoning in history"

Arsenic "is becoming the key environmental health problem of the twenty-first century." The reason for this statement is apparent in some parts of Bangladesh; West Bengal, India; Vietnam; and other Asian countries. The World Health Organization (WHO) advises a maximum permissible level for arsenic in drinking water

Figure 10.2 Arsenic-induced skin lesions. Credit: D. Chakraborti, Jadavpur University, Calcutta

of 50 μg/l, and recommends 10 μg/l. But in Bangladesh, more than 100 million people drink water containing more than 50 μg/l. In some Asian wells, arsenic levels exceed 3000 μg/l.

Why is this happening? Surface water in Bangladesh and in many other impoverished countries is too polluted with pathogens, and sometimes industrial chemicals, to serve as drinking water. So, 30 years ago the UN International Children's Emergency Fund (UNICEF) funded the drilling of wells to provide clean drinking water. When well water became available, infant mortality from diarrheal diseases dropped dramatically. The wells seemed a major success. However, in moist tropical environments, there is much organic matter buried in the sediments into which the wells were drilled. As this material decays it leads to chemical events that result in arsenic release into groundwater, and thus into wells.

Arsenic toxicity

Arsenic levels in Bangladeshi wells are high, but not high enough to be acutely toxic. Chronic toxicity is the problem. This meant that awareness of the poisoning was slow in coming. People began showing symptoms after they had drunk the water for 5 to 10 years. In Bangladesh, nearly one-quarter of the villagers examined in regions served by these wells had skin lesions, in a region where 59% of nearly 11 000 well-water samples contained more than 50 μg/l arsenic. Early symptoms are changes in skin coloration or many hard corns on the palms, soles, and torso. Drinking water with arsenic levels greater than about 300 μg/l resulted in skin lesions (Figure 10.2). Later, after the lesions were first observed, skin cancers began appearing. Later still, as people continued drinking the water for decades, lung, liver, and bladder cancers developed. Other major toxic effects also appeared, sometimes gangrene because arsenic is toxic to the nervous system, including the long nerve fibers in the limbs.

The nutrition connection

Recall from Chapter 3 that people who eat nutritious diets are less susceptible to poisoning. In well-fed people, even drinking water with arsenic levels of 400 μg/l may not cause lesions. In contrast, lesions occur at quite low levels in people who have poor nutrition, drink large quantities of contaminated water, or drink it over a long period. At the earliest stages of the poisoning, skin changes can be reversed by drinking clean water and eating nutritious food. Unfortunately, a great many poisoned people are poor and do not have access to either. In Bangladesh alone, 85 million people are at risk of developing cancer. This poisoning is a stunning tragedy.

Reducing the risk

An intense effort is under way to find ways to remove arsenic from water cheaply. Technologies already exist, but are too costly for impoverished countries. Techniques used to remove arsenic, or else to avoid water that contains it, include sand filters, harvesting rainwater or, in some cases, drilling deeper wells. In addition to choosing appropriate technologies, the WHO must closely oversee those that install them because corruption is so prevalent. Meanwhile, because wells with lower arsenic levels may be located far from their homes, many people continue to drink from arsenic-contaminated wells even though they are marked as unsafe.

Arsenic in wealthier countries

The situation is much less drastic in wealthy countries, but the United States too has many wells with water containing greater than 50 μg/l arsenic. A great many more have at least 10 μg/l arsenic. In the United States the maximum contaminant level (MCL) for arsenic in public water supplies was reduced to 10 μg/l in 2002 (from its previous 50 μg/l). However, the MCL does not apply to private wells, many of which have not been tested for arsenic. Even 10 μg/l arsenic may be risky: US researchers found associations between low-dose exposures to arsenic and increased risks of vascular disease, diabetes, and some cancers. A partial biological explanation for such associations was recently found. Laboratory studies on animal cells indicated that at low doses, arsenic may act as an environmental hormone. It does this by indirectly disrupting the action of the steroid hormone, cortisol, which is involved in regulating blood glucose levels and blood pressure.

Question 10.3

1. The "arsenic eaters" were Austrian smugglers who found that arsenic increased their physical endurance during difficult journeys across high mountains. They ate almost 0.5 g/day. This is a dose about ten times greater than that which can kill sensitive people. They began by ingesting about 10 mg twice a week. As their bodies acclimatized, they ate more, eating it with bacon to increase the absorption into their bodies. With this information in mind, consider Bangladesh. People here are ingesting low doses of arsenic compared with the arsenic eaters. What are possible reasons for the fact that they don't adapt in the same way as the Austrian smugglers?

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Chapter 11

Solid waste

> "The air and water grow heavier with the debris of our spectacular civilization."
>
> *Former US President, Lyndon B. Johnson*

Municipal solid waste (MSW) is but one of many wastes. There are also construction and demolition debris, municipal sludge, combustion ash, mining and drilling debris, agricultural wastes, industrial-process wastes including some sludge, hazardous waste, and others. Altogether the United States alone produces about 10.1 *billion* tons (9.2 billion tonnes) of waste each year. MSW is barely 3% of that gigantic stream, but it is important: each of us is intimately associated with it. Its composition and amount is the result of our behavior. Moreover, if we move back one step, the businesses producing the products going into MSW generate much of those billions of pounds of waste. In **Section I** we ask why we generate so much waste. We examine municipal solid waste, what is in it, and why it is of concern. **Section II** looks at setting priorities in how we manage waste – the waste-management hierarchy (WMH). Pollution prevention is at the top of the WMH, but this section also examines reuse and recycling, incineration, and landfilling. **Section III** moves onto international MSW issues starting with wealthy societies, and examines the major problems that wastes pose in developing and impoverished societies. It ends with the example presented by the city of Curitiba, Brazil.

SECTION I

Why do we generate so much waste?

Why does society generate so much waste? ■ Think about a metal. To obtain it, an ore is mined. However, the metal is but a small portion of even an enriched ore, so most of the mined material becomes waste. And the *overburden* – soil disturbed during mining – becomes waste too, as does the disturbed rock. If these are not handled properly, they

Table 11.1 How much waste is produced when making chemical products?

Industry	Product tons per year[a]	Waste/product ratio by weight
Oil refining	10^6–10^8	~0.1
Bulk chemicals	10^4–10^6	<1–5
Fine chemicals	10^2–10^4	5–50
Pharmaceuticals	10^0–10^3	25–>100

[a] 1 ton is equivalent to 0.9 tonnes.

Source: Poliakoff, M., Fitzpatrick, J. M., Farren, T. R., and Anastas, P. T. Green chemistry: science and politics of change. *Science*, **297**(5582), 2 August, 2002, 807–810.

are damaging materials. Refining and smelting of the ore produce more waste; so does manufacturing a product from the refined metal, and the product's disposal or recycling. ■ Or, consider the book in front of you. Starting in the forest, it produced waste when harvesting the wood to make it, more waste when the wood was transformed into paper, and yet more when the book was printed. ■ Think perhaps too about a head of lettuce. You discard its outer leaves. Before you bought it, other lettuce waste was produced by the farmer and the grocery store. A food waste such as lettuce is organic and can be composted. But often this does not happen.

For a sense of the amount of waste that producing a product generates, look at chemical products (Table 11.1). Recovering oil may pollute the surroundings of the well from which it was recovered and the oil-refining process also produces pollution. However, oil refining produces little waste – as compared with the mining mentioned above – because almost all petroleum is refined into products, albeit mostly burnable products. Only a few per cent of the oil is used to manufacture chemicals. "Bulk chemicals" are those produced in large quantities, such as benzene, and typically require only a few steps to make so, although the tons of waste produced per ton of product is much higher than in oil refining, it is still relatively low. Notice that fine chemicals and pharmaceuticals have a higher waste/product ratio. This is because it takes more steps to make them, and each step produces waste. ■ And what happens to a product, whether a chemical or a book, at the end of its useful life? Very often it becomes waste too. If recycled, that produces waste too. ■ Wealthy societies produce much more waste per person, but less-developed countries also produce staggering amounts. Even though a poor person produces less waste per person, there are so many people and typically poor waste management, so discarded wastes can be a major problem.

Municipal solid waste

You may not notice your contributions to air pollution. You may likewise casually send the contaminated water you produce down drains

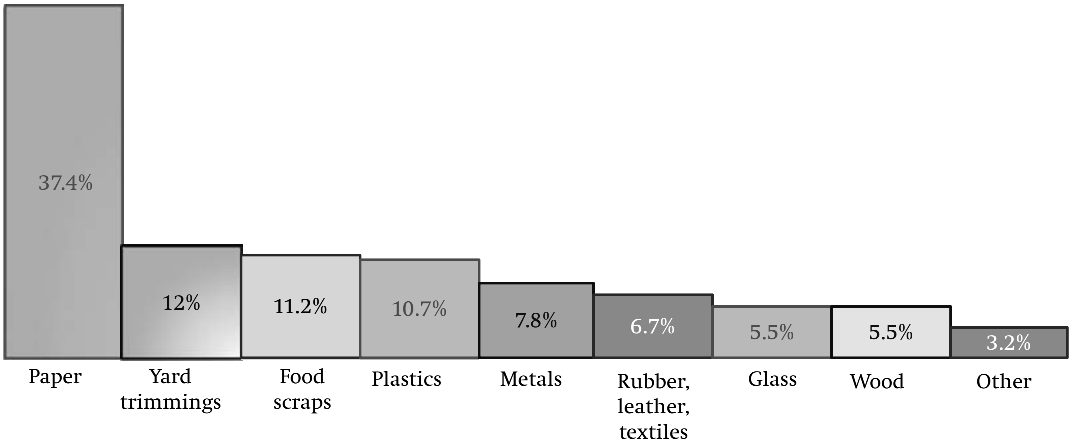

Figure 11.1 Materials in US municipal solid waste (2000). Source: US EPA Municipal Solid Waste, Basic Facts (see Internet resources)

and toilets. It's somewhat more difficult to ignore the solid waste that you produce. At a minimum, you must take it to a curbside. Historically, trash was the bane of many cities, as people dumped anything, including bodily wastes, onto streets. Solid waste still poses many problems.

What is in municipal solid waste and who produces it?

Household waste contains anything that we choose to discard. That includes still-usable and recyclable items: waste food, papers and newspapers, packaging, bottles, metal cans, batteries, grass clippings and other yard waste, clothing, furniture and appliances, paint and other discarded household chemicals (Figure 11.1). The "Other" category in Figure 11.1 includes appliances (white goods), furniture, batteries, and household hazardous waste (HHW). HHW includes residual paints, oily products such as automotive-maintenance products, and pesticides. For many years paper has been the largest proportion of MSW in the United States, currently about 37% by weight. This figure shows only what the US federal government views as MSW. Some states consider construction and demolition debris to be MSW too, where it equals about 12% by weight. Some communities consider other wastes to be MSW too, sludge from drinking-water-treatment and wastewater-treatment plants, septic-tank sludge, medical and slaughterhouse waste, and fast-food grease.

Households are only one contributor to MSW. Others generating MSW are institutions such as hospitals, government offices, schools, and prisons. Commercial businesses including restaurants, grocery stores, and offices are large generators too. And industries also generate MSW although industrial-*process* wastes are *not* MSW, and are handled separately (Chapter 12).

Why does MSW concern us?

Almost any garbage is at best unpleasant. It has unpleasant odors. Diapers and other sanitary items contain microorganisms, sometimes

Table 11.2 The lasting litter chart[a]

Product	Time needed to degrade in the open environment
Glass bottle	1 000 000 years[b]
Plastic six-pack holder	450 years
Aluminum can	200–400 years
Steel (tin) can	80–100 years
Rubber sole	50–80 years
Leather belt	40–50 years
Nylon fabric	30–40 years
Hard plastic container	20–30 years
Disposable diaper	10–20 years
Wooden stick	10–15 years
Cigarette butt	2–5 years
Hemp rope	1–14 months
Woolen cap	12 months
Cotton rag	1–5 months
Banana or orange peel	3–5 weeks
Paper	2–4 weeks

[a] Information source: E-Train (National Environmental Training Center for Small Communities).

[b] Glass bottles and metal cans are inorganic and do not biodegrade. They do slowly oxidize and crumble into tiny particles.

infectious; so do rotting food and yard wastes. HHW is only a small part of MSW, but enough to sometimes catch on fire, or injure workers whose skin or eyes come into contact with it, or who breathe in its fumes. However, a material need not be hazardous to present problems. Consider packaging, generated in large quantities. The composition of packaging may make it very difficult to recycle, or prevent it from biodegrading. And if it contains even trace amounts of hazardous metals, expensive controls are necessary to prevent metal emissions if it is incinerated. Or, if disposed of in a landfill, much MSW can last indefinitely. Even dumped in the open environment where there is sunlight, heat, and water, many items are long lived (Table 11.2). Even if MSW had no other problematic characteristics, the quantity generated creates difficulties for communities. The United States alone, with its 100 million households, generated 232 million tons (210 million tonnes) of MSW in 2000. In earlier times most families lived in rural locations, and household waste was not a major problem. But if every household today had to manage its own garbage, a crisis would quickly develop. The average American produces 4.3 lbs (2 kg) of MSW each day. For a household of four, this is 17.2 lbs (7.8 kg) per day or 3.2 tons (2.9 tonnes) per year. Handling waste is expensive whether it is incinerated or landfilled – or recycled. Americans pay about $30 billion per year for waste management, second or third only to the amount communities spend on education and police protection.

Box 11.1 Packaging paradox

If you examine products in a US grocery or retail store, you quickly see many products with unnecessary packaging. However, proper packaging performs valuable functions. Appropriate packaging reduces food spoilage and therefore the amount thrown away. In the United States, 15% to 20% of food is disposed of as waste from the time it leaves the farm until it reaches the consumer's table. In contrast, in very poor countries, foods lack protective packaging with the result that 40% to 70% is thrown away: it spoils during shipping and storage. Especially in impoverished countries where malnutrition is rampant, this truly is a waste.

SECTION II

MSW and the waste-management hierarchy

In 1976 the United States passed the Resource Conservation and Recovery Act (RCRA), a mammoth complicated law, which has been extensively updated over the years. The RCRA regulates all the wastes noted above including MSW and others too. As its name implies, the RCRA's purpose was to stimulate communities to manage waste in an environmentally sound way and to recover materials and energy. Recall the waste-management hierarchy (Chapter 2). Pollution prevention (P^2) – source reduction – is at the top of the hierarchy. Reuse and recycling is second in priority. Treatment is third; treatment serves two purposes, either reducing waste volume or reducing its toxicity. Disposal is at the bottom of the hierarchy; for MSW, disposal usually means landfilling.

Reducing MSW by P^2

P^2 is source reduction, and conserves resources. For MSW, P^2 means the volume of waste generated is lessened. Examples follow.

- Concentrated detergent. One small change may cause a cascade of results. See what happened when manufacturers began to design laundry detergents more concentrated than earlier detergents. The concentrated product weighs less, its volume is less, and fewer resources go into manufacturing it. Resources are conserved. Resources are further conserved because less packaging is needed and less packaging waste. And less energy is needed to transport a given amount of cleaning power, so energy is conserved and fewer pollutants are emitted. The consumer needs less of the concentrated detergent, so less detergent is discharged to the sewer.
- Light-weighting containers. While maintaining container strength, from the late 1970s to 1993 manufacturers reduced the weight of

plastic soda bottles by 25%, the weight of glass bottles by 31%, and the weight of aluminum containers even more. This *light-weighting* has all the advantages just noted for concentrated detergents. There are resource and energy savings, less pollution is produced, and less MSW is generated.

- Photocopying on both sides of the paper. This cuts the amount of paper used in half, halves paper waste, and has other of the advantages just noted. It also raises another important point – think that we could not photocopy on both sides of the paper if photocopiers were not designed to make "duplex" copying possible. Beyond this example of paper use, recognize that, for successful P^2, recycling, and reuse, we often need fundamental changes in product design. We must *design for the environment* (DfE). DfE is a major means of conserving natural resources, and promoting reuse and recycling. DfE will come up in this chapter frequently.

The examples noted can reduce the volume of MSW. How can we reduce MSW toxicity? Think about the hazardous metals, such as lead or chromium, present in some products, even those that are there in small amounts. Metals don't degrade, so even small amounts can build up.

- Printing. Newspaper and magazine printers traditionally used lead ink, and for colored sections hazardous-metal pigments. As soy bean and organic inks were developed, the use of metals has diminished.
- Packaging and plastics. Hazardous metals served useful functions in packaging and plastics, and could not arbitrarily be eliminated. But, when a search for alternatives was undertaken, it proved possible to find relatively benign organic molecules that could serve equivalent functions, and reduce the hazardous metals in these products.
- Lead products. Major reductions have been made in the content of the hazardous metal, lead in many products (Chapter 15). Similar effort is now directed toward reducing mercury in MSW.

Box 11.2 | Using our buying power

"Environmentally preferable products" are products and services with lesser impacts on human health and the environment as compared with others that serve the same purpose. Buying them represents P^2. One article's title[1] expresses an important approach – "Buying green: harnessing the incredible procurement power of governments, hospitals, colleges and America's biggest corporations to protect the environment." Some European countries and Canada use green labels to denote products judged environmentally preferable. In the United States, the EPA developed guidelines to identify environmentally preferable products, and federal agencies are asked to give buying preference to these. The expectation is that

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[1] Motavalli, J. and Harkinson, J. Buying green: harnessing the incredible procurement power of governments, hospitals, colleges and America's biggest corporations to protect the environment. *E, The Environmental Magazine*, XIII(5), September/October, 2002, 26–33.

government buying power will drive change: businesses wanting to sell to government agencies will modify their products to meet the guidelines. State and municipal agencies, universities and colleges can also use the guidelines. The EPA developed the following symbols to assist product identification.

Less hazardous. Buy a product with the lowest level of hazard, as indicated on the label, able to do the job. "Caution" refers to mild-to-moderate hazard. "Warning" refers to moderate hazard. "Danger" is the highest hazard (corrosive, extremely flammable, or highly toxic). "Poison" is also at the highest level, but refers specifically to toxicity. If low-hazard products are not available, or one must buy the more hazardous product, use the least-amount possible for the job and follow all precautions on the label. And use the product up entirely before throwing the container away.

Conserves energy. Buy energy-efficient products. In the United States the Energy Star label identifies these. Such products also save money on energy bills.

Recycled content. If the label says "pre-consumer" content, this indicates that manufacturer scrap was recycled. "Post-consumer" is materials used by consumers, such as paper, cans, glass, or plastic, and then collected after use and recycled.

Prevents waste. Buy the least amount of material possible to accomplish a task. When possible buy a product that is repairable, durable, refillable, or able to be reused.

Low volatile organic compounds (VOCs). Examine labels to look for low-VOC products. VOCs evaporate from many consumer products including office equipment, adhesives, carpeting, upholstery, manufactured wood products, paints, solvents, pesticides, and cleaning products. Because they can concentrate in indoor air, they are of special concern in offices and homes.

Conserves water. Choose water-conserving products and services such as automatic flushers and low-flow faucets and toilets. These also save money on water and sewer bills.

End of life. What happens to this product at the end of its useful life? Is it recyclable? If so, is it likely to be recycled? Will the manufacturer take it back? Might it be a hazardous waste that needs special handling?

Some states and cities go beyond the federal government. The state of Massachusetts and the city of Santa Monica, California are vigorously pursuing environmentally preferable products. These products have advantages in addition to environmental. If they conserve energy or water, they save money, certainly in the long run. In the workplace, using less-hazardous products can reduce liability, improve worker safety, and lower disposal costs. Products that are reusable, refillable, more durable, or can be repaired are more cost effective, certainly in the long run. See the EPA's web site (http://www.swmcb.org/EPPG/1_1.htm#prevents%20waste), which provides guidelines for specific goods and services, paper products, printing services, office machines, motor-vehicle products, cleaning products, carpets, grounds and building maintenance including using integrated pest management, and many others. But be aware that guidelines do not provide absolute answers. There are always instances where a product that is preferable in one respect is less desirable in others. The individual buyer must still make judgments.

You, in your individual life can make environmentally preferable purchasing decisions too. Buy durable goods, or a television set or appliance that can be repaired. Consider EPA guidelines when purchasing a car. Choose one with good fuel economy and maintain it well to reduce gasoline consumption, and reduce pollutant emissions from the vehicle. A clothing drier is a major energy user in the home, so purchase an energy-efficient model. Small steps are important. If you can use it up, buy a product in bulk quantity because the bulk product has less packaging per unit of product. Take fabric bags to go shopping rather than accepting new bags. Paper bags too can often be reused many times. This saves resources and prevents the pollution used to manufacture new products. There are hundreds of ways to reduce energy and water use, and to produce less household waste. Multiplied by hundreds of millions, the net impact is indeed significant.

Reuse

Reuse is P^2 also. In DfE, designers often work to develop reusable components in a product, and to find means to easily disassemble the product to obtain those components. The intent is that at the end of its life, a machine, e.g., a photocopier, should be easy to disassemble into reusable and recyclable parts. ■ Compare reusing a metal component in a product to recycling it. To recycle a metal component, the metal is melted, purified, and manufactured into a new product. All this requires energy, other resources, labor, and produces some pollution and waste. To reuse a component, it is used in its entirety, greatly reducing necessary inputs and pollution. ■ Many motor-vehicle parts are already remanufactured, which also is reuse. When you replace an alternator, clutch, or brake caliper in your car, the new part was probably *remanufactured* from a previously discarded one. To do this, the part is inspected, cleaned, and rebuilt to specifications that are at least as good as the original. This can save half the energy and labor as compared with a new part and reduces pollution; 70% to 90% of motor-vehicle parts are remanufactured. Other often-remanufactured products are telephones, toner cartridges, office furniture, even subway cars. ■ The challenge is to move toward an economy where we routinely reuse or recycle products that we now throw away – DfE must become routine.

Questions 11.1

Because of lack of education or of environmental awareness, we may overlook many opportunities to buy environmentally preferable products.

1. The United States, with 4.5% of the world's population, uses about half the world's detergent. People buy top-loading washers although front-loading machines require less detergent and less water, then run them with less than full loads of clothes. (a) In addition to the examples just given, how else can clothing be kept clean with less detergent? (b) In addition to saving detergent, what are other environmental advantages of front-loading machines?
2. How can we motivate individuals who can afford to buy larger models to buy a smaller car with better fuel economy?

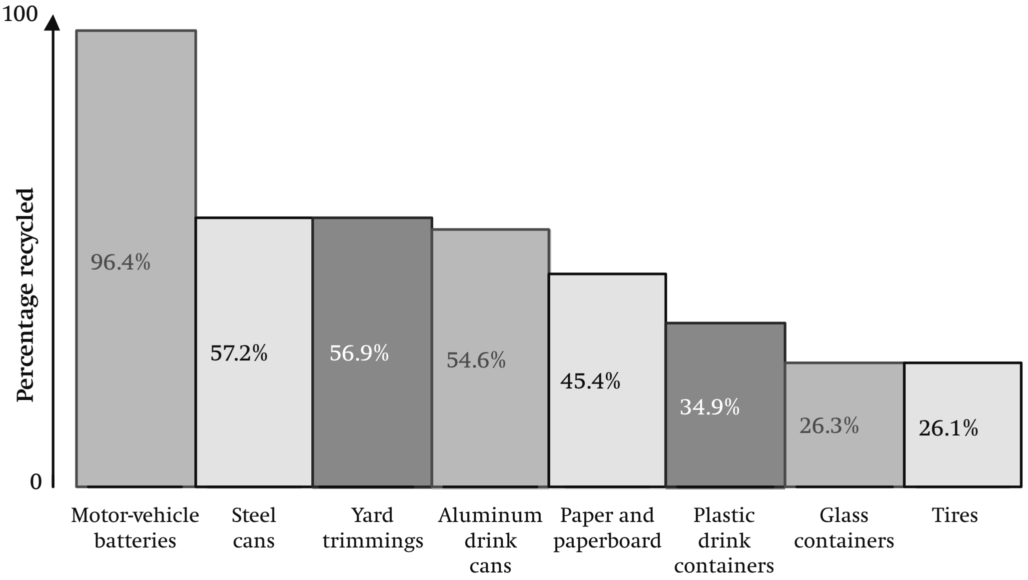

Figure 11.2 Recycling rates for common materials. Source: US EPA Municipal Solid Wastes, Basic Facts (see Internet resources)

3. The United States uses 30% of the world's paper production. Each year, every individual consumes the equivalent of 670 copies of the daily *New York Times*. How can we use less paper without detracting from quality of life?
4. Box 11.2 provides instances of how individuals can lessen their environmental impact. Provide at least three additional examples, especially those that you yourself might adopt.

Recycling

Recycling may be lower on the WMH than P^2, but it is vital. In 1997, 9000 US curbside recycling programs existed. These serve over half the population, and 84% of US cities. Recyclables could be dropped off at 12 000 other sites. Programs collect paper, steel (tin) and aluminum cans, glass containers, and sometimes, plastic containers and waste oil. In the ten states that charge deposits on beverage containers, recycling rates are higher than in states without deposits. Composting yard waste is one form of recycling. After recovering materials for recycling and composting, the 4.3 lbs (2 kg) of waste that each person discards each day falls to 3.4 lbs (1.5 kg). US recycling rates increased from 10% in 1980 to 22% in 1993 and 28% in 1997. Incinerating or landfilling is costly to a community. However, recycling – excepting high-value materials like aluminum – is accused of being more costly still. But, recycling typically uses less energy and produces less pollution than making a product from virgin resources, and saves resources. Recycling may also provide jobs not otherwise available.

Consider the recycling of some common materials, and see Figure 11.2.

- Aluminum. In 2002, little more than half of aluminum cans in the United States were recycled, this despite the fact that aluminum recycling pays for itself, it is a valuable metal, and aluminum cans are relatively easy to collect. Collecting aluminum foil, pie pans, lawn furniture, or aluminum used in siding, gutters, window and door frames is more difficult. Aluminum recycling has great environmental advantages – it uses 95% less energy than is required to mine it from bauxite, and reduces air and water pollution by 95%. And the United States has only about 1% of the bauxite ore from which aluminum is recovered – used consumer aluminum is the US aluminum mine.
- Steel cans. Recycling steel cans (also called tin cans because of their lining) saves 60% to 70% of the energy needed to produce them from ore.
- Paper. In 1999, the paper industry recovered 45% of the paper and paperboard used in the United States. Recycling increased to 48% in 2001 (49.4 million tons or 45 million tonnes), close to the 50% goal that industry had set for itself. Most recovered paper is post-consumer waste, not mill scraps; about half is old corrugated containers. To recycle more than 50% would be difficult as most good-quality paper is already recovered. However, poorer-quality paper can be composted or incinerated for its energy.
- Yard waste. Communities sometimes collect and compost yard wastes. Some homeowners compost their own. Compost can be sold to improve soil quality.
- Used oil. Of 1378 million gallons (5220 million liters) of used oil that the United States generated in 1991, only 4.1% was refined into new automotive oil – 13.4% was illegally dumped. Most of the rest was burned as fuel.
- Glass. Recycling glass saves energy, although not as much as for metals. About one-third of glass containers are recycled.
- Electronics. Used electronics are an increasing part of our waste stream, and responsible recycling is accorded to only a small portion. Electronics are part of everyday products, and electronic waste is not intrinsically hazardous. Yet its quantity and the way that electronic waste is often dealt with can make it hazardous. For this reason electronics waste and recycling is covered in Chapter 12. An increasing number of communities and states are banning computers and TV monitors from their landfills.
- Appliances. Many millions of used appliances are discarded each year: air conditioners, dishwashers, dryers, washing machines, refrigerators, freezers, stoves, microwave ovens, water heaters, etc. Some states ban appliances from landfills. They contain recyclable metal, but it must be removed from other materials.[2]
- Plastic. See Box 11.3.

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[2] Recall that recovering and purifying metals requires energy and produces pollution. It is preferable to use DfE to develop products in which component parts can be disassembled and remanufactured into new equipment.

Box 11.3 | Plastics[3]

The amount of plastic discarded in the United States has increased a striking 10% every year for 20 years. Plastics are used for containers and many other products, including component parts of motor vehicles, airplanes, and computers. In 1960, a motor vehicle used only 40 lbs (18.1 kg) of plastic; this had increased to 300 lbs (136 kg) by 1992. ■ Recycling plastics is environmentally valuable, as demonstrated by the polyethylene terephthalate (PET) in soft-drink bottles. Recycling PET uses 47% less energy than making it from raw materials. Most common plastics are thermoplastics; that is, they can be melted down and reshaped many times into new plastic products. ■ Only about 10% of the plastic in US MSW is recycled although about one-third of plastic soft-drink containers are recycled.

Recycling plastics poses challenges. One is the difficulty of collecting and separating the many types of plastics. It's even more difficult to recover plastic from complicated products such as a computer's plastic casing. Another is that individual polymers are often incompatible when being processed into new products. ■ In 2002, New York City suspended glass and plastic recycling because recycling them didn't pay for itself. Used plastics are valuable, but businesses say they cannot be assured of a dependable supply. Moreover, the price that plastic recyclers receive varies with the price of oil, so there is no dependable price. Ten US states have bottle bills, laws mandating that deposits be paid on plastic, glass, and metal containers. Companies making containers vigorously resist extending bottle bills to other states although this would increase the dependability of a recycling supply. Meanwhile in the United States, about 4 billion PET soda bottles a year go into landfills or become litter. ■ The situation for recovering plastic casings from computers is worse and is deteriorating. About 315 million computers will have been discarded by 2004 containing about 2 million tons (1.8 million tonnes) of plastic. ■ Discarded plastic – once collected and sorted – is valuable and goes into products such as Tyvek™ (disposable medical suits and insulation), fleece garments, plastic "lumber," and water-repellent coatings for shipping boxes, and asphalt too. But products made from recycled plastic are often more expensive. Plastic box coating costs $2.50/lb (0.454 kg) compared with $0.50/lb for wax coating. However, compared with other products, plastics may be more durable, perform better, or the product weighs less than its counterparts. For example, plastic "lumber" can last much longer than real wood. However, people resist the higher prices of recycled plastics.

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[3] Six resins are used to make most plastic containers and packaging. Each has a code number often found on the container. Code numbers are as follows. Code 1, polyethylene terephthalate (PET), a strong, clear polymer used to make soft-drink bottles and medicine containers. Code 2, high-density polyethylene (HDPE), often found in milk, juice, and water bottles and in containers for household cleaners such as detergent. Code 3, polyvinylchloride (PVC) or vinyl (V) is found in clear films used, e.g., to protect meats; it allows air to pass through it, clings, and is puncture resistant; vinyl is also found in pipes and sporting goods. Code 4, low-density polyethylene (LDPE) is flexible and strong; it is commonly used in grocery and garbage bags, and in shrink and stretch film. Code 5, polypropylene (PP) has a high melting point; so it can be filled with hot products, which can then cool within the bottles; it is also used for caps and yogurt containers. Code 6, polystyrene (PS) is a hard, often colorless plastic; in its expanded form, *foam* PS provides shipping protection for products such as electronics.

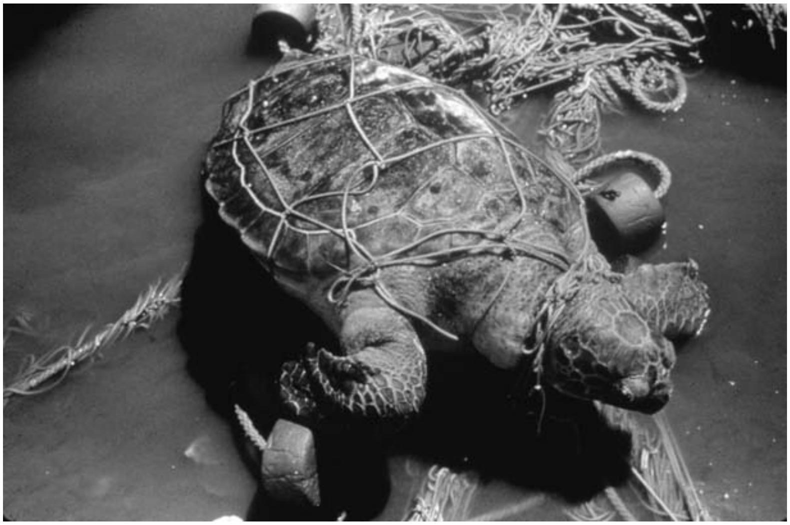

Figure 11.3 Sea turtle killed by entanglement in marine debris

Plastics are massively accumulating

Plastics are amassing in the world environment. Thor Heyerdahl made a famous 1947 sailing voyage described in his book *Kon-Tiki*. When in 1970 he again sailed the oceans, he saw enormous amounts of oily wastes on the waters along with trash and plastic debris. More recently, the Algalita Marine Research Foundation found a dramatic increase in plastic debris when they made a 6000-mile (9700 km) transect voyage across the north Pacific Ocean: for every 1 lb (0.454 kg) of the vital organisms, plankton they captured in their trawls, there were, on average, 6 lbs (2.7 kg) of plastic flotsam. This included tons of drifting nets, bags, and common plastic household items. These articles are lost or deliberately dumped by vessels or washed out to sea from coastlines, and often present as plastic bits of various items. In the north Pacific Ocean, many birds, mammals, fish, and sea turtles die each year after entanglement in plastic debris (Figure 11.3); or, when swallowed, plastics clog digestive systems. One study found plastic, assumed to have been fed to them by parent birds, among the skeletons of albatross chicks. Sea turtles may confuse plastic bags with jelly fish and swallow them. Plastic debris also damages coastal habitats. No organisms can biodegrade the plastic. Indeed, the microscopic plankton, so vital in the food chain also ingest tiny bits of plastic.

Positive signs

■ Carpets. More positively, US carpet manufacturers have signed a National Carpet Recycling Agreement, to promote carpet recycling. DuPont reclaimed 36 000 tons (32 700 tonnes) of carpet in the 1990s, a great start, but minuscule given that billions of pounds of carpets are landfilled each year along with other plastic floor coverings. ■ Electronics. Electronic equipment – with its plastics – is clogging landfills. Under pressure, some companies have hesitatingly started take-back programs for discarded computers, but people do not find it easy to access their programs. And plastics made from recycled computer casings are of low value. IBM has begun using the same plastic in several of its products; this allows easier recycling, and recycling into more valuable products. One of IBM's computers has plastic parts made almost entirely from recycled resins, and IBM has a stated goal of using recycled resins in most of its products. ■ Research. Investigation is ongoing to develop better technologies to recognize and separate the various types of plastics, and to better remove glues and labels from plastics. Perhaps the greatest impediment to recycling, also being addressed in research projects, is convenient collection and separation. *In the meantime*, plastics need to be kept out of the environment. This means not throwing plastic away irresponsibly, and working for effective community collection programs. See Box 11.7.

Recycling can go far beyond the recycling examples shown in Table 11.3. With an adjustment in perspective, recycling becomes a routine part of life. Meanwhile, more materials are landfilled or incinerated than recycled. Recycling has problems too. Consider paper; it contains coaters, fillers, and pigments, which must be removed before the paper fiber can be recycled. These extraneous components, not currently reusable, are landfilled. And working in recycling facilities is not easy. Workers are injured, sometimes killed in accidents involving equipment used to recycle cans, bottles, and paper. Injuries occur even in industrialized countries. Imagine then recycling carried out on dumps such as the one described below in the Philippines (see Section III). There is also the same resistance to having recycling facilities in the neighborhood as there is for landfills and incinerators; the "not in my backyard," or "NIMBY," phenomenon.

- Composting and "biotreatment". Organic wastes such as grass, leaves, and other yard wastes can be composted. So can most food wastes. Composting is considered to be recycling. It is also a form of *biotreatment* because microorganisms degrade the organic materials to yield a soil-like product. Composting food wastes with worms is another form of biotreatment. In addition to composting, other examples of beneficially using biotreatment are seen in this text: microorganisms degrade organic matter in landfills, in secondary wastewater treatment, and can treat some hazardous wastes (Chapter 12). More broadly, the degradation of wastes by microorganisms, worms, and other creatures is a major natural service.

Box 11.4 | Eliminating car discards

Reuse/recycling

About 75%, by weight, of a discarded automobile is reused or recycled. Much of the iron is recycled. Lead-acid batteries, starters, tires, generators, and other engine parts are also typically reused or recycled. The rest of the car, "fluff" (plastics, liquids, and glass), usually goes to a landfill. The European Union is mandating extended producer responsibility to motor vehicles; that is, manufacturers must take responsibility for their vehicles over their whole life cycle, including the end of their useful lives. US manufacturers who sell cars in Europe must also comply. The European companies, BMW (Germany), Fiat (Italy), and Renault (France) have developed facilities to dismantle, shred, and recycle the components of their discarded cars. They share information and technology, and each accepts used vehicles from the others.

Life-cycle assessment

The Swedish car manufacturer, Volvo did a life-cycle assessment (LCA) on a Volvo to evaluate its full impact – from the extraction of raw materials used to manufacture the vehicle, its manufacture, and its use and disposal. LCA results can be of great help to effective DfE, designing more environmentally sound vehicles. DfE includes designing for disassembly, and designing for reuse and recycling of component parts.

Promoting recycling

Society can promote recycling in many ways. *Promoting technology development* is one. Plastics contain a number of different resins, which, if mixed together, are useful in manufacturing only a few products. As technology develops to collect and sort plastics more efficiently and economically, each can be recycled to specific higher-value uses. New technologies may also find more uses for mixed plastics. *Economic incentives* can promote recycling, for example when government subsidizes businesses that use secondary (used) materials rather than virgin ones. *Promoting social and behavioral changes* can improve recycling. Governments can: support recycling and waste-reduction education in schools; sponsor television, radio, or newspaper advertisements promoting recycling; and emphasize the important role of citizens in sorting trash from recyclables or buying products with recycled content. *Governmental mandates* may help to enhance recycling. They can: require government offices to give preference to environmentally preferable products when making purchases (Box 11.2); and require citizens to pay deposits on beverage containers, tires, car batteries, furniture, or appliances at the time of purchase. A bottle bill to promote container return is an example of this; so is a law charging a tax on each new tire sold, the revenue is used to subsidize recycling.

■ Businesses making voluntary changes. In cooperation with the US EPA WasteWi$e program, L. L. Bean of Maine formed teams to reduce waste. Bean's set waste-reduction goals and an action schedule to meet them. As the name WasteWi$e implies, waste reduction can provide financial rewards. ■ The EPA has urged businesses to preferentially buy recycled products when making purchasing decisions, and manufacturers to include recycled content in their products. ■ Another voluntary action is to use DfE. Designers work to develop products that are easily disassembled into reusable or recyclable parts. They use fewer types of plastics in products, label plastics for easy identification, and use plastic in ways that allow their easy separation from other components at the end of the product's life. ■ It is harder to persuade businesses to design for durability and easy repair of a product, because they want to sell more not less. ■ Another voluntary program in the United States is take-back. Sony and several other corporations have begun pilot take-back programs for consumer electronics including television and computer monitors. In Europe, there are mandatory take-back programs.

Table 11.3 Recycling is not just about paper and cans

Organic wastes	Yard and kitchen waste can be composted in backyards or community composting programs. Properly treated sewage, paper-mill sludge, and animal waste can be used as a fertilizer or soil amendment.
Old clothing and textiles	In the nineteenth century, paper was made from cotton rags, and new clothing from discarded woolens. Today, clothes are recycled by selling them at yard sales or donating them to others. Old clothing is often exported to less-developed countries. Clothing that cannot be reused may be processed into rags or mixed into asphalt to make roof shingles.
Disposable diapers	A child may use 5000 diapers by the age of 30 months. A number of cities worldwide, including Toronto, recycle them. Wood pulp is extracted as are the super-absorbent polymers and plastics.
Grease	Fast-food restaurants discard billions of lbs per year of used cooking grease. This can be processed into ingredients of poultry and cattle feed, or used as lubricating oil. Another growing use is as a biodiesel fuel for motor vehicles.
Television sets and telephones	European television and glass manufacturers formed a consortium to recycle picture tubes from discarded television sets. Germany's largest telephone company has formed a consortium to recycle telephones.
Building materials	Wood and other materials from old buildings can be recovered, and often reused. Builders can incorporate materials into new construction – discarded tires, plastic bottles, or metal cans, but it may be difficult to obtain building permits. Incinerator ash can go into concrete, and old newspapers into insulation.
Toilets	California had a program to crush discarded toilets into an aggregate, which was added to concrete for road-building projects.
Telephone poles	Old telephone poles contain creosote and pentachlorophenol, wood preservatives that are now banned. These made recycling impossible until a *bioremediation* process was developed. Poles are chipped into small pieces and composted with microorganisms that can degrade creosote and pentachlorophenol. Clean wood fiber is then sold to paper mills.
Fluorescent lamps	Fluorescent lamps are more energy efficient than incandescent bulbs, and the United States uses at least a half a billion lamps yearly. They contain a glass tube, aluminum end caps, inert gases, phosphor powders, and 20 to 50 mg of mercury. Because of the mercury, many states ban them from MSW landfills. Businesses have developed techniques to recover and recycle the mercury, aluminum, and other components. Newer lamps contain much less mercury.
Radioactive materials	Without a long-term storage site, the nuclear power industry recycles metal from used radioactive pumps into new pumps used within the industry.
Old subway cars	These can be remanufactured into new cars. Those that cannot be reused can be submerged along coastal areas for use as artificial reefs.
Recycling as an automatic way of thinking	• San Francisco converted a former Air Force base, the Presidio, into a park; 70 acres (28.3 ha) of asphalt and concrete from its air field were crushed and reused beneath pathways and parking lots. • Curitiba, Brazil converted an 11-acre (4.5 ha) garbage dump into a botanical garden. It converted a derelict quarry into a Free University of the Environment, which holds courses for everyone on land-use and environmental issues.

Questions 11.2

1. Instead of a flat fee to haul a household's waste away, regardless of the quantity discarded, some communities charge per bag. (a) Are there possible disadvantages to this? Explain. (b) If your community had a bag charge, what steps, if any, would you take to reduce waste?
2. Consider this quotation from Agenda 21, a document resulting from the 1992 World Summit: ". . . the major cause of the continued deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialized countries." Do you agree with this assessment? Explain.
3. The Union of Concerned Scientists carried out risk assessments of common activities. (a) They found that an individual's major environmental impact comes from the use of transportation. How do transportation decisions affect the environment? (b) Eating meat is another activity having a major environmental impact. Why does eating meat have more adverse environmental impact than eating grains, fruits, and vegetables?

The fate of disposed MSW

MSW that is not recycled is typically landfilled or incinerated (Figure 11.4). In the modern facilities of the twenty-first century both these options are carefully regulated in developed countries.

Incineration

The purpose of treating waste is either to reduce its quantity or its toxicity, or both. Combusting MSW in an incinerator does reduce volume by up to 90% and weight by 75%. Ash uses only about one-third as much landfill space as does MSW itself. ■ Proponents of combustion believe it is important to MSW management, especially in large-population centers with limited landfill space. ■ But it is argued that it does not reduce toxicity: with the organic materials of MSW burned away the metals in the ash are more concentrated than in the MSW. Most, about 90%, of the ash from incineration is landfilled, and metals may leach from the landfill. Landfill leachate[4] is usually captured and treated, but cases exist of leachate reaching and contaminating groundwater. To allay this concern, some communities remove as much metal as possible from MSW before burning it. Ferrous (iron-containing) materials are often valuable and recovered before burning, and the ferrous fraction in combustor ash is recovered for recycling. Burning lead-acid batteries from motor vehicles is prohibited in many states. Instead, batteries are recovered and recycled. It is harder to remove small button batteries, which have been a major source of mercury in MSW. Although it is expensive to do, it is

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[4] "Leachate" is water that has percolated through a landfill, dissolving contaminants as it goes.

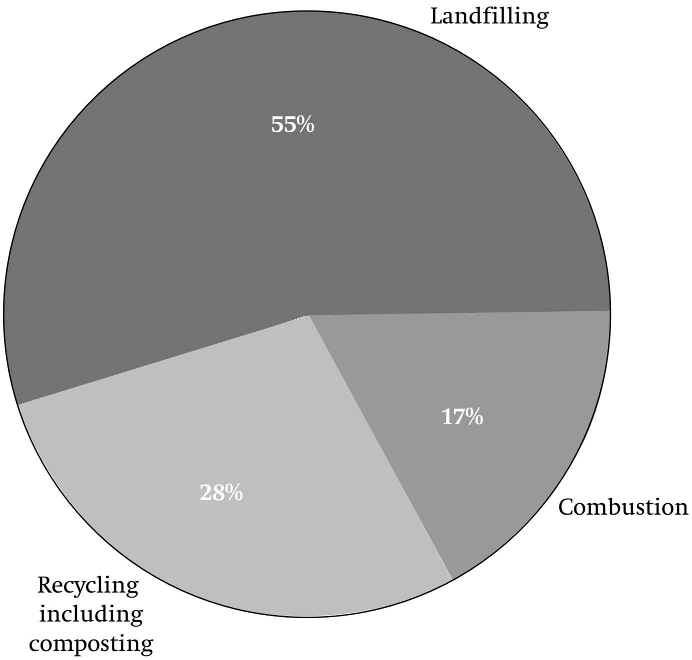

Figure 11.4 How MSW is managed in the United States (1997). Source: Franklin Associates, 1998 report to the US EPA (see Internet resources)

possible to vitrify (convert into a glass-like material) the metals in the ash. Vitrification greatly reduces leaching. ■ Some do not consider ash toxic. Metals are more concentrated in the landfill leachate, but the solids content is lower than in leachate from raw MSW. Ash is also free of the microbes and organic materials that make garbage objectionable.[5] And, because it is free of organic material, the ash does not generate methane gas as garbage does. Methane has sometimes led to explosions; it is also a greenhouse gas. However, methane is often collected from large landfills and used as a fuel. MSW incinerators are highly regulated in developed countries with strict regulations on dioxin and hazardous-metal emissions, including mercury. In 1997, the United States burned 17% of its MSW.

However, concentrated metals are not the only problem with ash. Combustor ash is rich in mineral salts. In small amounts, salts are not a problem; however, in the quantities generated by burning large amounts of MSW, they pose the same problem as posed by the piles of salt used to control road ice in winter. Salts dissolve in water and run off into surface water or percolate into groundwater. Thus, even ash without hazardous metals still has salts such as those of calcium, magnesium, and potassium. Proper landfilling remains very important to prevent leaching into the environment. There are some uses for ash that can minimize the amount landfilled. Several European

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[5] Tiny amounts of organic chemicals are formed during incineration and are found in *fly ash*. "Fly ash" is that which could "fly" into the atmosphere if not captured. The organic chemicals formed include dioxins and furans, which make it especially important to capture fly ash. Dioxins formed can be much minimized in a well-operating incinerator.

countries, after first stabilizing the ash to prevent leaching, incorporate it into aggregate for use in road paving. Another use is incorporating ash into cement and other building materials. In the United States, most ash is landfilled. However, if traditional resources become more expensive or better technologies develop, more may be used.

Energy value of MSW

Combustion of MSW can produce steam and electricity, and recover some of the fuel value of plastics, paper, and other carbon-containing wastes. Certain materials have especially good fuel value. Polystyrene, a plastic used in foam, has an energy value of 17 800 Btu/lb, and waste tires 15 000 Btu/lb. Both values are much higher than wood, which has an energy value of 6700 Btu/lb. However, when everything in MSW is burned, the fuel value is much less. Wet garbage must be heated before it even burns. To generate electric power from MSW, a combustor must be well supplied with fuel-rich materials such as paper and plastics. This may hinder recycling by taking away otherwise recyclable materials. The value of a recyclable material must be high to promote recycling as opposed to incineration. Only a few per cent of plastics are recycled. But, plastics are made from petroleum – and most petroleum is burned as fuel with only about 4% going to chemical manufacture. Some argue that, we already burn more than 90% so why object to burning a few additional per cent?

There are different types of incinerators. ■ Some are mass-burn; that is, they burn everything in MSW although some or all recyclables may be removed first. ■ Another category burns so-called "refuse-derived fuel" (RDF). In RDF, non-combustible wastes such as ferrous materials, glass, and grit are first removed. ■ A recent technology pyrolyzes MSW (decomposes it at high temperatures in the absence of oxygen) converting it to gases, which can be burned for fuel (methane, hydrocarbons, hydrogen, and carbon monoxide). A variation on pyrolysis is thermal gasification in which a limited amount of oxygen is present. This also produces combustible gases. ■ An even more recent technology introduces MSW into very high temperature, up to 5000 °C, plasma-arc furnaces. Combustible gases are created, reportedly enough to fuel the plant. Other gases created are potential pollutants, and must be captured. In the plasma-arc process, molten metals are tapped off and cast into ingots for recycling. Almost everything else is converted into glass-like substances that can be processed into bricks, tiles, and other materials for home and industrial use.

Sanitary landfills

In the United States, 55% of all MSW was discarded to landfills in 1997, a figure down from 81% in 1980 (Figure 11.5). ■ In addition to MSW, landfills often hold construction and demolition debris, municipal sludge, agricultural wastes, combustion ash (unless it has been determined to be hazardous), non-hazardous mining and drilling debris,

Figure 11.5 MSW in a landfill (much trash is already covered over). Source: US EPA Library of Environmental Images

and non-hazardous industrial process wastes. ■ Hazardous wastes, excepting those from households cannot be landfilled. Leachate. A sanitary landfill is engineered to minimize water infiltration. Nonetheless leachate is produced, and must be collected and treated. Large facilities (such as New York City's Fresh Kills Landfill, closed in 2001) produce enormous amounts of leachate. In the early years after a waste has been landfilled, leachate contains foul-smelling organic compounds; this is collected and treated to meet EPA standards before it is discharged. Methane gas. Because a typical landfill has little oxygen, anaerobic microorganisms (those not requiring oxygen) degrade its organic materials. Anaerobes produce methane gas. This must be managed to prevent explosions. However, methane is a valuable fuel and many landfills collect and use it as a fuel.

Bioreactor landfills

Organic materials can biodegrade. However, this happens very slowly in the usual landfill because the landfill microorganisms that can degrade organic materials, lack the water and nutrients that they need to carry out this function. Indeed, landfills are often criticized as places to store mummified trash: consider the life span of common items even in the open environment (Table 11.2). In a landfill, "mummified" foods and newspapers can be found intact many years after being disposed of. In the future, such problems may be overcome using *bioreactor* landfills. Instead of treating and releasing landfill leachate, it is circulated back into the landfill. Leachate is rich in organic chemicals. Kept within the landfill, the leachate provides energy and nutrients to the microorganisms that degrade organic wastes. Recirculating leachate greatly hastens *landfill stabilization*. A landfill is considered stabilized after most of the organic material has biodegraded. At that point, it releases much lower amounts of organic contaminants into the leachate and generates much less methane gas. In an ordinary landfill, stabilization can take many years. However, if leachate is recirculated, this can happen in 5 to 10 years. Furthermore, in the years before stabilization, the bioreactor landfill produces much more methane gas than a typical landfill. This can be captured and used as fuel. A traditional landfill, once full, is capped with an impermeable layer and its discharges are monitored for 30 years. However, if waste is quickly stabilized in a bioreactor landfill, it may be possible to reduce monitoring to as little as 10 years. Moreover, once organic materials degrade, landfills could be more easily mined for recyclables. One obstacle to bioreactor landfills is that they are initially more expensive because they need machinery and pipes to recirculate leachate.

Landfill siting

■ Dumps. Historically, trash was dumped in the open, often close to rivers or over groundwater. In fact, dumps were sometimes deliberately placed on river banks so that spring floods would wash the trash away. Open burning of trash in dumps continued into the 1970s.

■ Landfills. Starting in the 1980s, strict regulations came into force in the United States as to where landfills could be sited, and how they could be built, maintained, and monitored. When possible, landfills are sited over near-impermeable clay to provide natural containment for the waste. To further trap the water percolating through them, landfills have synthetic liners, and a collection system to recover and treat the leachate. Monitoring wells built around the landfill are regularly sampled to detect leaks. Such landfills, built according to strict regulations and carefully engineered standards, are clearly safer than "dumps." Even so, there is concern that leachate may escape into the environment before wastes have degraded to the point where leakage is of much less concern. However, a carefully-constructed facility may remain leak-free past the point where leakage poses a problem. Such sophisticated landfills are very expensive to build. From that perspective, they provide a waste-reduction incentive – the more expensive it is to landfill, the more attractive are recycling options.

■ NIMBY. The "not in my backyard" (*NIMBY*) phenomenon is a potent force making it extremely difficult to site landfills or incinerators. This is true although the United States has a much lower population density than many other countries (Figure 11.6). There are several reasons for the NIMBY phenomenon. A modern landfill must be large to be cost effective. But a small community doesn't need a large landfill, nor can it afford to build one. Instead, a regional landfill serving

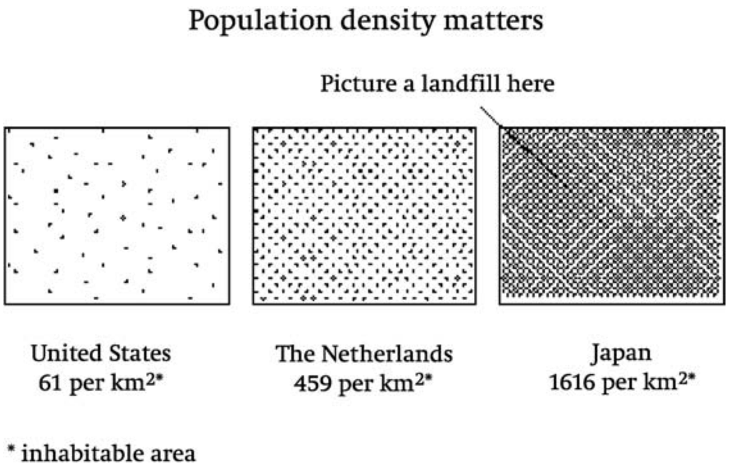

Figure 11.6 Siting a landfill in a densely populated locale is difficult. Credit: Dr. Cynthia F. Murphy, University of Texas, Austin, 13 July, 2000

many communities is built. People have no sense of ownership in a landfill many miles distant, and communities hosting landfills feel resentful at taking others' trash. Moreover, truck traffic is associated with pollution, noise, and road degradation. Property values often go down. And landfills and other waste facilities are disproportionately built in poor and minority communities. As these communities became more socially aware, they increasingly object. Another reason that many oppose landfills is that they leave our mummified trash for future generations to manage.

Box 11.5 | We can reduce but not, usually, eliminate waste

Ideally we reuse or recycle materials, but except for metals, which can be recycled indefinitely, recycled materials eventually become trash too. Some materials, we cannot recycle at all. Combustion lowers waste volume, but leaves ash. Waste will thus remain with us for the foreseeable future – "I am, therefore I pollute." *But* we can redefine wastes as byproducts, and find uses for these byproducts.

Landfill mining

Sometimes *landfill mining* is useful. Materials are excavated from a landfill because they have value or because space is required for more waste. Instead of closing landfills, it is sometimes possible to extend their lives. Many older landfills contain up to 70% dirt and only 30% trash. Even if recovered materials have little value, removing the dirt creates space to landfill more trash. And, the dirt itself can serve as a dump cover. In Germany, during landfill mining, recovered materials go to a sorting plant, where wood, rubble, and metals are removed. Materials not worth recovering are incinerated or returned to the landfill. In the future as some raw materials become more expensive or scarce, landfill mining may become more common. When landfills are full, they are either left wild or are developed into parks or golf courses.

Box 11.6 Batteries and the WMH

Manufacturing a disposable battery takes about 50 times more energy than the battery provides when used. Yet US residents purchase and throw away 3 to 4 billion batteries a year. This uses resources inefficiently and contributes metals, including hazardous metals, to MSW complicating both combustion and landfilling. How can we manage batteries more efficiently?

- P^2. Avoid unnecessary batteries. Buy toys and appliances that don't need them. In another form of P^2, manufacturers have reduced or eliminated mercury and cadmium from their batteries. However, button batteries, used in watches, calculators, hearing aids, and hospital and military equipment, still often contain large quantities of mercury or silver. These have been a major source of mercury emissions when MSW is incinerated. Buy mercury-free, zinc-air button batteries when available.
- Reuse. Purchase rechargeable batteries. They require energy to recharge, but much less than required to manufacture them from virgin materials. Solar rechargeable batteries are useful in regions with plentiful sunlight.
- Recycling. Valuable *button batteries* can be recycled. Some button-battery collection programs exist in the United States and Europe, and some jewelry stores encourage their return. The *nickel–cadmium (Nicad) batteries* used in appliances and lap-top computers are recyclable. Newer appliances have been designed to allow removal of Nicad batteries for recycling, and consumers are encouraged to return them at the end of their useful lives. US manufacturers do not usually consider *household batteries (A, C, D, and 9V)* as worth recycling although the Swiss have done so for years. US attitudes are changing, albeit slowly, and battery-recycling programs are appearing in an increasing number of places.
- Disposal. In the past, rechargeable batteries were eventually discarded, and Nicad batteries were a major source of nickel and cadmium in MSW. This may change if recycling takes hold. Most disposable household batteries are indeed disposed of, but some communities collect them to divert the metals away from MSW incinerators and landfills. In the future, more may be recycled.

Questions 11.3

1. The above description of batteries and the WMH does not mention treatment. (a) Can incineration of batteries be considered a treatment? Explain.
2. Individuals can avoid buying unnecessary batteries. They can buy rechargeable batteries, and make the effort to recycle batteries. What actions could (a) government and (b) manufacturers take to encourage the use of rechargeable batteries, and of recycling or at least responsible disposal?
3. Evaluate your own battery use. (a) How many do you use? What kind? Do you recycle them? (b) What circumstances would induce you to make sure your batteries are recycled? (c) Are there circumstances that would induce you to use fewer batteries?

SECTION III

MSW internationally

OECD countries

The average person in the 29 prosperous member nations of the OECD[6] produces about 3 lbs (1.4 kg) of MSW a day. Without preventive action this is projected to increase to 3.8 lbs (1.7 kg) a day by 2020. Thus, the OECD believes that our trash generation requires attention now. The situation is more serious than the difference between 3 and 3.8 lbs (1.4 and 1.7 kg) indicates because population is also growing – although the population of some Western European countries is stagnant the population of one member country, the United States, is growing at about 1% a year. Currently, about 66% of OECD garbage is landfilled, less than 20% is incinerated, and only 18% is recycled. The OECD targets for 2020 are: 50% landfilling, 17% incineration and 33% recycling.

Waste in less-developed countries

The OECD countries produce more waste per person than poor countries, sometimes very much more. But MSW is a major problem in poor countries too. To make matters worse, garbage production is expected to double within 20 years. This is happening in countries that have few resources with which to deal with the waste, and where waste contributes not only to unpleasant conditions, but to disease as well.

Box 11.7 | "Throwing away" a ship

Shipbreaking is the dismantling of old ships for scrap metal and other valuables, once carried out in the United States and Europe. In the 1970s as labor costs and environmental regulations increased, the industry moved to Korea and Taiwan. Lastly, it moved to the poorest countries including India, Bangladesh, and Pakistan. Each year, about 700 come to the end of their lives; of these, 90% end up in impoverished countries. There, workers dismantle them by hand using tools such as hammers and blowtorches, with little worker or environmental protection. Bangladesh wants the steel in the ships, which is several times cheaper to produce by re-rolling from dismantled ships than milling it from fresh ore. Ore must be imported because the country "is a river delta with no mineral deposits, just sand and earth."

Figure 11.7 shows a step far along in ship dismantlement: recovering copper from wiring by burning off its rubber casings. Photographer Claudio Cambon comments that this sight is common in shipbreaking yards. This "dramatically polluting activity . . . sadly typifies the level of safety and protection available to workers and

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[6] The Organization for Economic Cooperation and Development (OECD) has 29 member states, mostly developed nations. These include the United States, the United Kingdom, other Western European countries, Australia and New Zealand, and Japan.

Figure 11.7 Shipbreakers burning rubber casing of copper wire in Chittagong, Bangladesh. Credit: Claudio Cambon, Marina Del Rey, California (Copyright, 1998)

the environment not only in shipbreaking, but in all of Bangladesh, a poor country with little infrastructure of any sort." The work is dangerous and polluting, but the jobs are in demand. Referring to hazardous materials in the ships that could affect their health, workers told Cambon "why worry about what might kill me 20 years from now when I can't see from here to one month from now, because I can't feed myself and my family without this job?" Cambon does not believe that a poor shipbreaking yard should bear sole responsibility for worker safety and pollution. He supports an approach in which the shipyard that builds a ship and each successive owner of the ship pay a fee into a fund. The fund would be used to help create and maintain an infrastructure for ship dismantlement and for safe disposal of toxic substances such as PCBs.

China

If developed countries struggle to manage MSW, imagine the problem in China, a nation with more limited resources, but with at least 1.2 billion people. Waste is described as an "ever-growing ocean," increasing by about 10% a year. Lacking enough treatment and disposal facilities, waste is often dumped in the open, causing soil, air, and water pollution. Dumping also wastes land in a country needing every bit of its land. In 1995, China enacted the Prevention and Control of Solid Waste Pollution to the Environment Act. This mandated source reduction, recycling, treatment, and environmentally sound disposal. Unfortunately, the law was poorly enforced, there was too little money to build processing facilities and train workers, the public was not educated, and recyclables continued to be mixed with garbage. Hongtao Wang and Yongfeng Nie, of Beijing's Tsinghua University urged that regulations be improved and *enforced*. They advocate a "polluter pays system" as an incentive for businesses and individuals to reduce their waste generation, and separate out reusable and recyclable items. China has now begun a new effort through a

5-year plan that sets new goals and a schedule to implement them. It is developing regulations and standards, training waste-management personnel, establishing college-level research and training in material recovery and reuse, composting, incineration, and landfilling. It has purchased some needed technologies, started demonstration projects in some cities, and established an information network. Although central administration is involved, local sanitation departments oversee the implementation. No one foresees quick changes, especially with the limited funding available. Indeed implementation has made a slow start. Chinese waste experts believe that an urgent need exists for cooperative projects with developed countries to develop technologies and equipment suited to China's specific needs.

Philippines

In the Filipino city of Manila, people who live in regular housing typically have a garbage collection service. However, the dumps to which the garbage is taken in Manila – as is also the case in many other impoverished cities – are not the "sanitary landfills" seen in industrialized countries. Many thousands of Manila's 10 million residents work in its garbage dumps – they also live and eat there. They scavenge recyclable paper, plastics, bottles, and metals, and often eat waste food as well. Many children and whole families are among the workers. An estimated 60 000 people are at the Payatas dump and another 100 000, whose livelihoods are based on "the recycling-waste chain" live around the dump. Scavengers are exposed to broken glass and cans, and to the pathogens that multiply in the garbage. They work without masks, gloves, sometimes even without shoes to protect their feet, and no first-aid stations. They continue working despite the fact that, in 2000, about 100 people died and another 150 "disappeared" at the Payatas dump after a flashflood and fire destroyed many tents and shacks. Environmentalist Alvin Sotero says that, "They are, for the most part, regarded as little better than the trash they handle" by better-off Manilans. He asks what Manila would do without the services of these scavengers whom he regards as "the city's environmental heroes." Not all is bleak. "Shanties are hung with flowerpots and posters of basketball stars like Michael Jordan and local movie idols. There are tiny barbershops and ice-cream stands . . . births and weddings and school graduations." These conditions are not unique to the Philippines. They are found in many impoverished places.

Box 11.8 | Littering – the "white pollution"

In many Asian countries, littering is a major problem. The average Asian consumes less than citizens of richer countries, but except for Japan and Singapore, litter is everywhere, especially plastic litter. And Hong Kong despite its riches is, as author J. Tremblay notes, "plagued by litterbugs." (See Further reading.) Individuals don't take responsibility for their own waste. Many governments do nothing about it because they see more serious problems demanding attention. The companies in

Asia who manufacture plastics believe that litter isn't their problem either, although BASF has a program in which employees visit schools to talk about their products. Dow Chemical believes civic education is the key to changing individual behavior; it contributes to the International Coastal Clean-up project sponsored by the Center for Marine Conservation, a US organization. In this effort, volunteers clean up beaches and waterways yearly. In 1999, the project involved nearly 500 000 volunteers in 60 countries including 9 in the Asia–Pacific region. But more is required than picking up the litter – they need to reduce it. Some believe the chemical industry should take the lead in reducing plastic litter; this would greatly help its own image at the same time. A few Chinese cities have banned the use of, e.g., polystyrene foam lunch boxes. And Singapore, one of the world's cleanest cities has strong and strictly enforced penalties for littering.

In 2002, to the dismay of manufacturers, Taiwan banned plastic bags and polystyrene-foam containers. It did this because plastic bags choke Taiwan's landfills, and littered discarded plastics are unsightly, block drainage channels, and cause other problems. Moreover, Taiwanese incinerators were not designed to burn plastics, and dioxin is released when plastics are burned. The government found it easier to ban plastic bags and containers than set up a recycling system. Thick plastic bags are still available because the government believes they will not be thoughtlessly discarded. Plastic bags are also still used for pharmaceuticals and perishable goods such as bakery products. However, without plastic bags, many believe that more paper will be used instead, and paper litter will replace plastic litter. The chemical industry is warning that plastic processors may move to mainland China, taking its 50 000 jobs with it.

Questions 11.4

1. What is the environmental advantage to Taiwan of ridding itself of plastic?
2. (a) Is there an environmental advantage of using more paper rather than plastic? Explain. (b) Is there an environmental disadvantage? Explain.
3. What appears to be missing from Taiwan's program?
4. Taiwan is relatively rich. How can it, and poorer nations, increase citizen awareness of the environmental impacts of their actions, and provide incentives to change behavior?
5. What more should manufacturers of plastics be doing?

Garbage and slums

The United Nations estimates that between 835 million and 2 billion people worldwide live in slums in cities such as Bombay, Bogata, Cairo, or Manila. The number of people in slums increases by the day. In Asia, more than half the urban population lives in slums, often in extreme poverty. City governments don't usually collect their garbage so it piles up, litters neighborhoods, and fouls local waters (Figure 11.8). Residents sometimes burn garbage piles to reduce their volume, creating noxious fumes when they do. The garbage plus, often, excrement are sources of pathogens and disease. Residents want better conditions for themselves, and often attempt to create

Figure 11.8 Intoxicated man asleep in uncollected trash (Nairobi, Kenya). Credit: Lana Wong (Wong., L. *Shootback: Photos by Kids from the Nairobi Slums*. London: Booth-Clibborn Editions, 1999)

them. However, they typically lack title to the plots holding their make-shift houses and, in some places the government periodically bulldozes such homes or otherwise evicts the inhabitants. ■ There are several positive steps, however. Some governments are working to give slum inhabitants legal title to their habitations. Self-help organizations of slum dwellers have been formed in many cities. In Bangladesh, Waste Concern, a non-profit organization is promoting waste composting. With assistance from outside organizations, it pays garbage collectors in the city of Dhaka to sort the trash they collect, and compost its organic waste. This practice curbs disease, creates jobs, and produces useful compost. The organization is working to spread their project across the whole of Bangladesh.

Curitiba

One city, Curitiba Brazil provides a model of how successful recycling and waste management can exist even in a poor city, even one where the population tripled in less than 30 years as people flooded, and continue to flood, into the city. The city has a "Garbage That Isn't Garbage Initiative" that led 70% of households to sort recyclables for collection three times a week: organic waste into one bag, and paper, metal, and glass into another. Two-thirds of the materials in the recyclables bags are indeed recycled, furnishing half the cost of the collection system. In poor sections of the city where collection trucks cannot get into the unpaved allies, there is a "green exchange." Citizens bring their bags to trucks and in exchange receive tickets to exchange for food or items such as school books. Much of the food for the exchange is from the excess produced by local farmers. An "All Clean" project clears litter from hard-to-reach areas especially those near the rivers, which the city works hard to avoid polluting. Children receive environmental education starting from an early age and, indeed it is incorporated into the whole curriculum. People flocking into the city, far from being evicted, may receive small plots of land and building materials with which to build dwellings. When possible, they are hired for clean-up and recycling jobs. "In Curitiba, everything is recycled" including old buses and buildings. This approach to "waste" is part of a wider attitude to good governance that has also set up a model transportation system and non-polluting industries, and that uses land in a way that avoids polluting it or the rivers and air around it. Curitiba decided to treat its citizens ". . . most of all its children – not as its burden but as its most precious resource . . ."

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Chapter 12

Hazardous waste

> "I've worked with indigenous people on all continents but Antarctica, and one thing they all agree on is the Earth is sacred. We're the only ones who look at it as a commodity."
>
> *Ethnobiologist Dr. Paul Cox*

A hazardous waste is one that is ignitable, corrosive, reactive, toxic, or more than one of these. As with municipal solid waste, hazardous waste is also a small percentage of the 10 billion tons (9.1 billion tonnes) of total wastes that the United States generates each year. But, hazardous waste has been abandoned at many thousands of sites in the United States, and around the world. At these sites, hazardous substances evaporate into the air, contaminate soil, seep into groundwater or run off into nearby water. **Section I** of this chapter overviews hazardous waste, its characteristics, locales of hazardous-waste sites, and who generates hazardous-waste. **Section II** takes us to the waste-management hierarchy as applied to hazardous waste. **Section III** deals with hazardous-waste sites, evaluating their risk, and how human exposure occurs. **Section IV** moves on to reducing the risk of hazardous-waste sites. It examines clean-up methods including bioremediation. **Section V** takes us to hazardous-waste dumping in impoverished locales and the international accord negotiated to combat this practice. One waste still moving into developing countries is electronic discards, a steadily rising waste stream. We look at how we can reduce that flow.

SECTION I

Introduction to hazardous waste

Characteristics

Hazardous waste is a legal term. As defined by the US Resource Conservation and Recovery Act (RCRA) a hazardous waste has one or more of the following characteristics – it is ignitable, corrosive, reactive, or toxic.[1] See Box 12.1.

- A "toxic" substance can adversely affect the health of living organisms exposed to it. Examples are arsenic and cyanide, pesticides and many metals.
- A "corrosive" substance can cause grievous injury at the point of contact, i.e., the skin, eyes, lungs, or mouth. Strong acids and alkalis are corrosive. So are chlorine and hydrogen peroxide. The concentration of chlorine (as hypochlorite) or hydrogen peroxide found in household products is not corrosive, but much higher concentrations are often used in industrial and laboratory settings.
- An "ignitable" or "flammable" substance can catch on fire. It is a fire hazard. Petroleum distillates and many organic solvents are ignitable. Ethyl ether, once used as an anesthetic is highly flammable, and its volatility adds to its danger.
- A "reactive" substance reacts violently with water, air, or other substances. Ethers (chemicals used in industry and laboratories) can form explosive peroxides if left sitting in their containers for years. More familiar reactive substances are dynamite, gun ammunition, and firecrackers. In the household, chlorine bleach and ammonia if mixed together will react to form toxic fumes.

Hazardous waste is considered *solid waste* under the RCRA, but hazardous waste includes containerized liquid or gaseous wastes. Some wastes that might be hazardous are exempted by law, such as certain mining wastes and coal combustion ash. Household hazardous waste (about 1% of total hazardous-waste) is exempt even if it contains the same chemicals that are regulated when industry produces them. Two other potential hazards of waste are addressed by separate laws: infectious agents and radioactive materials.

Box 12.1 | Remember that a hazard differs from a risk

For a hazardous waste to be a risk, a person, animal, or plant must be exposed to it, and exposed in a way that can cause harm. Unless the waste has escaped into the environment, the greatest hazard is usually to the workers handling it. Corrosive, ignitable, or reactive wastes can also harm materials, as when a corrosive "eats" though a metal drum.

Locations of hazardous-waste sites

In earlier years, hazardous-waste generators placed the waste in lagoons or trenches such as at the infamous Love Canal (Box 12.2). Other means of disposal included injecting it into underground wells, or disposing of it along with municipal solid waste. ■ Dumping metal drums containing hazardous waste onto land, usually at rural sites,

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[1] These same characteristics apply in the definition of a hazardous chemical. Indeed, it is hazardous chemicals that often become hazardous wastes.

also occurred and still occurs in some countries and corrosive wastes sometimes ate through the containers and escaped into the environment. ■ Military bases are a major locale of hazardous-wastes sites. ■ Other generators legally released hazardous substances into waterways with little or no treatment, with the result that in some places, there are also water-based hazardous-waste sites. In Chapter 14, you will read of a 40-mile (64.4 km) section of the Hudson River, which is a hazardous-waste site due to polychlorinated biphenyl (PCB) contamination. ■ Often a whole production site became a hazardous-waste site. Many sites date from the nineteenth and early twentieth century, such as locations where municipalities produced *town gas* from coal or oil to use for lighting; many became modern hazardous-waste sites. Other old sites include nineteenth- and twentieth-century mines, contaminated with hazardous metals and acid waste.

Over time, the location, even the existence, of many old sites was forgotten. Casual disposal was thoughtless rather than malicious. All kinds of waste were once disposed of casually. So long as the population was small and industrial and military operations relatively small, such disposal was largely disregarded. But operations producing hazardous wastes grew in size and number. At the same time, human populations grew and cities spread out over the countryside. It was inevitable that people and hazardous waste would make contact.

Hazardous-waste sources

Large petroleum refineries and chemical manufacturers generated up to 90% of the about 270 million tons (245 million tonnes) of hazardous waste that the United States produced in 1998. This amount has been falling over the past 10 to 15 years. These facilities treat and dispose of about 90% of this waste on their own premises. Manufacturers of metal products are another large generator producing wastewater with high-enough concentrations of metals to be hazardous. Military operations generate hazardous waste, sometimes in large amounts; so do government agencies, especially the Department of Energy. Hospitals, many universities, and commercial laboratories, generate smaller quantities of hazardous wastes. Other small-quantity generators include small businesses such as gas stations, photographic developers, dry cleaners, sometimes even beauty parlors. Although the definition of hazardous waste varies, the UN Environmental Program estimates that 300 to 500 million tons (272 to 454 million tonnes) are produced worldwide each year.

Household hazardous waste

Paint residue is the household hazardous waste produced in the largest amount. Others are paint thinners and strippers, pesticides, cleaners and polishes that contain petroleum distillates, and alkaline drain and oven cleaners. Even some discarded cosmetics, such as acetone nail-polish remover are considered hazardous waste. MSW incinerator ash, although its origin was household trash, may be deemed hazardous waste. This happens if the ash does not pass an EPA-specified leaching test. ■ A familiar hazardous waste is *used oil*, which is both ignitable and toxic. Many "do-it-yourselfers" change the oil in their cars themselves. Of this, the EPA estimates that at least 150 million gallons (568 million litres) a year ends up in landfills or sewer systems; yet more is poured on the ground. The EPA could regulate used oil as hazardous waste, but with millions of do-it-yourselfers, this is impractical. Instead, the EPA developed standards for commercial handlers: if the oil is to be disposed of, it may be treated as hazardous waste. It is treated less strictly if it is for recycling.

SECTION II

Dealing with hazardous waste

Pollution prevention

Once waste is generated, it is too late for P^2 – unless the system is set up to treat the "waste" as a useful byproduct that is fed into another process (see Industrial symbiosis, Chapter 2). And, hazardous waste can stimulate P^2 because companies want to avoid the costs of regulations, treatments, and legal liabilities. Thus, they work to minimize the use of hazardous chemicals that might become hazardous waste. Ways in which this can be done are overviewed in Chapter 18 (green chemistry and green engineering, using design for the environment to design more environmentally benign chemicals, etc.) Chapter 2 has examples of P^2, recycling, and reuse.

Recycling and reuse

Some industrial hazardous wastes can be reused or recycled. The many hazardous organic solvents used in industry can, after use, be purified and reused. The reuse–purification process may be repeated many times. Many consider this P^2. However, some waste is necessarily produced because the contaminants removed during purification become waste. A company sometimes produces a byproduct that is useful to another company, and sells or gives it away. Such byproducts are sometimes advertised in order to find buyers.

Treatment

There are two major reasons for treating waste: one is to reduce the volume of the waste; the other is to reduce its toxicity. Four types of treatment are shown in Table 12.1: thermal, chemical, physical, and biological. Some reduce volume, some reduce toxicity, and some accomplish both. ■ Reducing volume. As with municipal solid waste, incineration is often used to reduce the volume of hazardous waste. However, in Table 12.1 notice other methods that can also lead to decreased volume. ■ Reducing toxicity. There are many variations of the methods shown in the table that lead to reduced waste toxicity.

Bioremediation

Bioremediation uses living creatures to treat waste, often to reduce toxicity and sometimes to reduce volume too. Developing bioremediation

Table 12.1 Treatments for hazardous wastes

Treatment	Examples
Thermal	*Incineration* can destroy organic substances. If metals are in the ash, the ash may still be hazardous waste, but its volume has been much reduced. *Stabilization* is a process in which a metal-containing waste is heated to high temperatures and melted. After it solidifies into a hard mass, it is difficult to leach metals from it. Thus, in many cases it may safely be placed in a landfill.
Chemical	*Neutralization* takes an alkaline or acidic substance, and converts it to a neutral form. An acid is neutralized with an alkali, or an alkali with an acid. After neutralization, the waste is no longer hazardous unless it has other hazardous constituents. *Precipitation* is often used to treat a metal solution. A substance is added that leads to the metals becoming insoluble and precipitating out. The precipitate too may be hazardous, but waste volume is much reduced. If enough metals precipitate from the solution and are carefully removed, the solution may no longer be hazardous.
Physical	In *filtration*, a liquid is separated from a solid using a membrane. The liquid goes through membrane pores. The solid particles are retained on its surface and its volume is much reduced. If enough hazardous material is filtered out, the liquid coming through the membrane (the filtrate) may no longer be hazardous. *Distillation* is sometimes used to separate a mixture of liquids. The mixture is heated. Lower temperatures drive off the more volatile substance, leaving behind those with higher boiling points. Depending on the chemicals and the success of the distillation, the waste remaining may or may not be hazardous. Volumes of some of the components can be reduced too.
Biological (bioremediation)	Microorganisms degrade certain organic hazardous wastes using them as nutrients. Certain plants take up and concentrate metals from soil or water (*phytoremediation*). Some microbes also concentrate metals or change the metals to less noxious forms.

Once chemicals are separated from one another (whether by precipitation, filtration, or distillation) they are better managed than if they remained in mixtures. However, the separated chemicals may still be hazardous waste, and need further treatment.

methods is of great current interest because it works with natural systems and is sometimes of lower cost than physical, chemical, or thermal methods. A necessary precondition is that the waste must not be poisonous to the creatures used. ■ Reducing volume. Bioremediation can sometimes reduce volume. Certain plants and trees take up and concentrate a hazardous metal from soil or water in a process called “phytoremediation”. ■ Reducing toxicity. Microbes can reduce waste toxicity by degrading its organic chemicals to less-toxic chemicals. In one application, microbes are grown on filters and hazardous organic gases are passed through them. In some cases this degrades 95% to 99% of the gases. Research to develop microorganisms that are bioengineered for specific uses is of great interest. More is seen below on using bioremediation to clean up hazardous-waste sites.

Disposal

Disposal is at the bottom of the waste-management hierarchy. But, unlike municipal solid waste, hazardous waste cannot legally be landfilled in the United States until treated to destroy its toxicity, or stabilized to prevent its hazardous components from leaching. More than one treatment may be needed to accomplish this before it can be landfilled. ■ Some waste is disposed of by injecting it into deep underground wells within well-understood geological formations. A permit to inject hazardous waste into a well requires that the waste must not contaminate underground drinking-water sources for 10 000 years. This of course can be difficult to prove, and concern remains that groundwater could become contaminated. Complex and costly regulations plus potential liability, limit such disposal.

A tracking system

In the United States, hazardous waste is regulated from "cradle to grave". ■ If a hazardous waste leaves the facility generating it then an identifying document, a *manifest*, goes with it. ■ If the waste is going to a storage facility, the storage facility receives a copy of the manifest. ■ When the waste goes to a treatment facility, it receives a copy too. ■ Finally, the disposal facility receives a copy and sends a copy back to the generator. The generator then sends a copy to the EPA or a state agency. ■ Such a procedure assures that a paper trail documents the waste every step of its way, from cradle to grave. In Chapter 18, you will see a new approach, "cradle to cradle". Its intent is to assure that a material doesn't become waste.

SECTION III

Hazardous-waste sites

A hazardous-waste site is a site where uncontrolled release of hazardous substances has occurred, or is likely to occur. In the late 1970s, Love Canal became a notorious example of people and hazardous waste coming together (Box 12.2). Fortunately in today's United States, a site is usually found and evaluated before a situation reaches such an extreme point.

Evaluating a newly identified site

Many questions need answering when investigating a hazardous-waste site. What chemicals are present? What type of soil is it and how does water drain from the site? Is there evidence that contamination of surface or groundwater has occurred? How close is the site to human dwellings? Are there routes – air, water, or food – by which human exposure to the waste could occur? By 1997, more than 40 000 uncontrolled hazardous-waste sites had been reported in the United States The EPA investigated these sites, and believed that most did not require federal action. These were left to the individual states to remediate. The EPA deemed that about 1300 sites were high risk. These were placed on a National Priority List (NPL) over which the US EPA would oversee remediation. Love Canal was one of the first high-risk sites identified (Box 12.2).

Box 12.2 | Love Canal

Built in the 1890s, Love Canal was never used. Later, starting in 1942, the Hooker Chemical Company disposed of 22 000 tons (19 960 tonnes) of hazardous waste there, including halogenated organic chemicals and pesticides; some of this waste was contaminated with dioxin. Hooker's disposal methods were standard practice for that time. The US Army was reportedly responsible for about 25% of the waste. In 1953, Hooker filled in the site, and capped it with a layer of protective clay. At the request of the city of Niagara Falls, Hooker sold the property to the Board of Education for $1. The deed warned that hazardous chemicals were buried at the site, but the city later said that Hooker had not informed it of the hazards of the wastes. Occidental Chemical purchased Hooker in 1968 before Love Canal's problems became known, and it was Occidental that was held responsible for paying a significant portion of the clean-up costs.

In 1954, the Board of Education built one school next to the landfill and another directly over it. It sold some of the land to a developer, who put up hundreds of houses, some directly around the landfill. In the 1960s, a highway bordering the development was built. As it was built, roads and sewers were constructed over and also directly through the Hooker site, and its protective clay cap was partially excavated, allowing rainwater to seep into the waste. It was this highway that created the greatest problem by blocking the normal path of groundwater migration through the area. The result was that the waste, and an increasing amount of groundwater and rainwater, became trapped in a clay "bathtub" (the canal). This began overflowing – along with its contaminants – into the basements and back yards of homeowners living near the canal. People complained of odors in the 1960s, and the complaints increased in the 1970s as the water table continued rising. In 1980, the federal government in an emergency action, bought several hundred homes, and evacuated their occupants. Homes closest to the canal were destroyed, and the rest were sealed off. The status in 1993: ■ Top. Love Canal's 40-acre (16.2 ha) cap had been repaired and sealed with a thick layer of clay plus a high-density plastic membrane. Contaminated soil had been removed. ■ Around. Eight-foot-high (2.4 m) fencing had been built around the site. ■ Drainage. A drainage system directing leachate to a treatment system had been built. ■ Bottom. The site's bottom rests on low-permeability clay, which greatly retards downward movement of leachate. Occidental Chemical assumed responsibility for maintaining the leachate system.

These efforts cost about $325 million, but only contained the site without remediating the waste. The site must be maintained for many years. Officials believed that it no longer threatened human health or the environment. They decided to redevelop the area and sell, at reduced prices, the homes that had not been destroyed. The new inhabitants as well as the former ones who had never moved are of two minds: some, especially those who had refused to leave their homes, believe the risks were greatly overstated and blame the city and state for disrupting the canal; others believe the site still poses unacceptable risks. Many court cases are still pending filed by people who believe the contamination caused their illnesses. An ongoing study examines the health of local people, but there is no way of measuring the psychological effects on those involved. One resident stated that "Niagara Falls is no longer the honeymoon capital but the toxic-waste capital." It was Love Canal that led the US Congress in 1980 to pass a law governing abandoned hazardous-waste sites. This is called the CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) or just the "Superfund."

Questions 12.1

1. Did the city of Niagara Falls bear any responsibility for what happened? Explain.
2. (a) Should a business be held liable for a hazardous-waste site clean-up even though the damage was caused by an earlier owner? (b) If not, who should be held responsible?

Health threats of hazardous-waste sites

Most-often-found chemicals

Four metals, lead, arsenic, mercury, and cadmium, are among the ten chemicals most commonly found at hazardous-waste sites. Another four are volatile organic chemicals: benzene, vinyl chloride, chloroform, and trichloroethylene. The other two are PCBs (described in Chapter 14) and benzo[*a*]pyrene (BaP); a polycyclic aromatic hydrocarbon (PAH) described in Box 5.7. The Agency of Toxic Substances and Disease Registry (ATSDR) has identified many other industrial chemicals at hazardous-waste sites too, more than 2000.[2]

How can exposure occur?

Human exposure to chemicals at hazardous-waste sites may occur through air, drinking water, soil, or food (Figure 12.1). Follow the possible exposure pathways through air, food, soil, and water.

- Air. If the waste spilled onto the soil includes volatile organic chemicals (VOCs), these can evaporate. Direct inhalation by humans would ordinarily be very small unless they live extremely near the site (or unless on-site workers were unprotected).
- Food. Evaporated VOCs could settle onto vegetation (such as the trees and corn plants shown here). Animals may eat the contaminated vegetation or grain. Later, humans may eat contaminated meat, vegetation, or grain.
- Soil. This is not usually a direct exposure source for humans, but could be for plants and animals on site.
- Water. Spilled waste could percolate into groundwater or – not shown – run off into surface water. Groundwater that is used for drinking is considered the most likely exposure route for those living near to sites.

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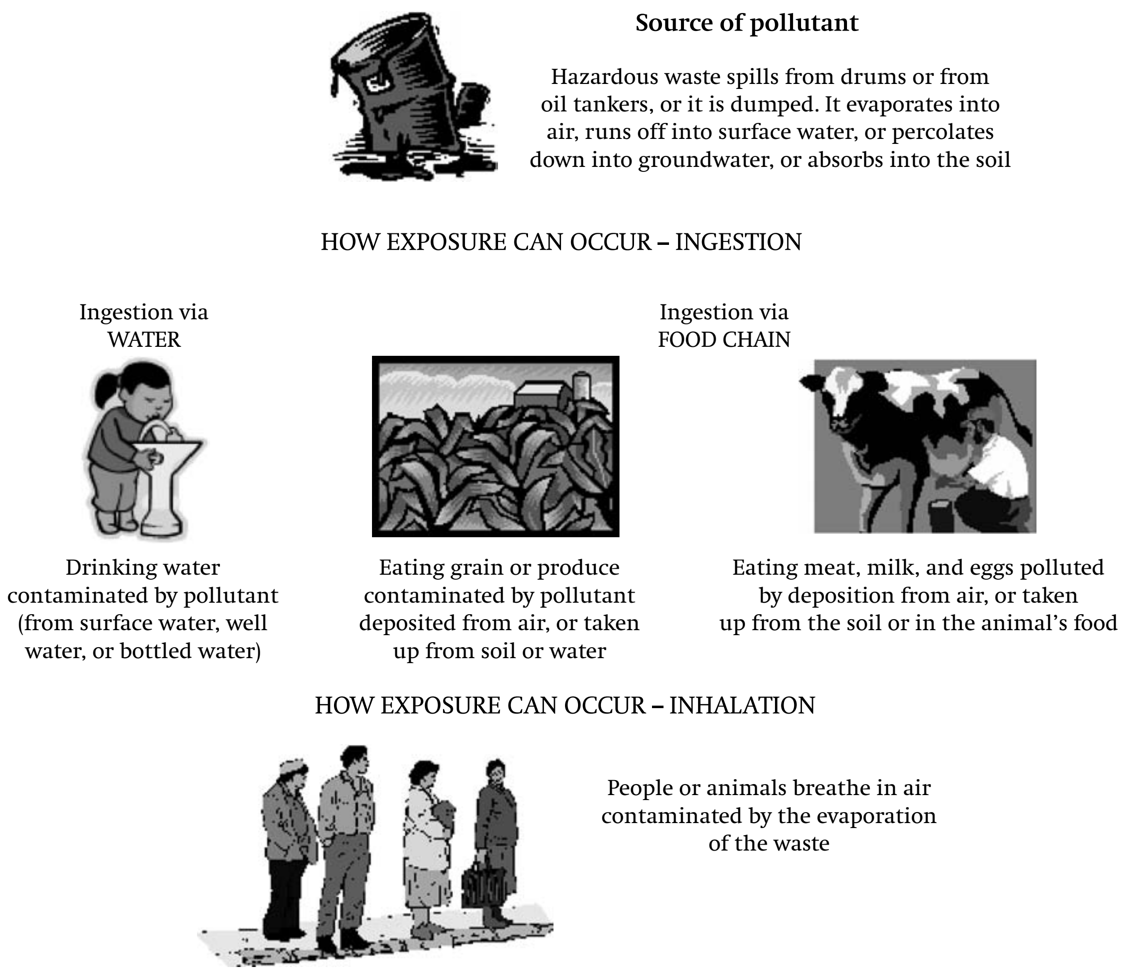
[2] The ATSDR is an agency created, by the Superfund law, to deal with the risks posed by hazardous-waste sites. Each of the 2000 chemicals has at least one hazardous-waste characteristic; that is, it is toxic, corrosive, ignitable, or reactive.



Source of pollutant

Hazardous waste spills from drums or from oil tankers, or it is dumped. It evaporates into air, runs off into surface water, or percolates down into groundwater, or absorbs into the soil

HOW EXPOSURE CAN OCCUR – INGESTION

Ingestion via WATER

Drinking water contaminated by pollutant (from surface water, well water, or bottled water)

Eating grain or produce contaminated by pollutant deposited from air, or taken up from soil or water

Ingestion via FOOD CHAIN

Eating meat, milk, and eggs polluted by deposition from air, or taken up from the soil or in the animal's food

HOW EXPOSURE CAN OCCUR – INHALATION

People or animals breathe in air contaminated by the evaporation of the waste

Figure 12.1 How exposure to hazardous waste can occur. Source: US Agency for Toxic Substances and Diseases Registry

Health-risk assessments

Before taking action to clean up a hazardous-waste site, we first assess possible health risks to people living near the site. We need answers to many questions. What is the route of exposure (ingestion, inhalation, skin absorption, or food)? What is the level, frequency, and duration of exposure? What are possible health effects? Who is exposed? In particular, are children exposed? About half of the NPL sites that were evaluated, starting in 1992, were deemed to pose a health threat to nearby residents. Another quarter were not believed to pose a threat. The other sites had "indeterminate risk;" that is, it wasn't clear if they presented a risk to nearby residents.

Many epidemiological studies have been done on people living near hazardous-waste sites. The Agency of Toxic Substances and Disease Registry estimates that 20 to 40 million US citizens live within 4 miles (6.4 km) of a hazardous-waste site. About 4 million live within a mile (1.6 km). Some studies indicated that these people have a small-to-moderate increased risk of cancer and birth defects, but others showed no adverse health effects. Nonetheless, taken together, some find the results troubling. However, all the studies were based on how close to the hazardous-waste sites the people lived. Studies were not based on actual measured exposures to chemicals. To correct this, current studies are looking at individuals who were actually exposed. This can be determined (Chapter 4, Section I) by monitoring urine, blood, and tissue samples for chemicals found at those sites.

Example of another type of hazardous-waste site

Some hazardous-waste sites that confront us were created by leaking, underground storage tanks. Years ago, most tanks that stored petroleum and other flammable chemicals were above ground. Because these posed fire hazards, underground tanks became popular. But over years of burial, the tanks corroded and leaked, contaminating surrounding soil and, sometimes, groundwater. At one time, more than 2 million underground tanks were believed to exist in the United States, located beneath gas stations and industrial operations. The EPA has worked with states to remove tanks that were leaking, and to clean up the contamination caused by them. To prevent future leaks, the EPA now requires underground tanks to meet specific design, construction, and installation requirements and to have leak-detection and leak-prevention systems.

Federal sites

NPL hazardous-waste sites are not the only high-priority sites. Even more important are the 20 000 sites for which the federal government itself bears responsibility. Some were produced by US Department of Defense Operations (military bases) and many others by the Department of Energy (weapons complexes). The Departments of Agriculture and Transportation are responsible for a smaller number of sites. Some are described as “toxicologically very complex” because they contain not just the usual hazardous wastes, but radioactive wastes too. These pose particularly difficult and expensive problems. Estimates of clean-up costs are staggering, perhaps $500 billion to $1 trillion, spent over a period of at least 30 years. It is unlikely that all can be cleaned up, certainly not to “pristine” conditions. Priorities will have to be set with the highest-priority sites being those presenting risks to people living near them. So how are the health threats evaluated?

Questions 12.2

1. Explain how a hazard differs from a risk.
2. Proximity to a hazardous-waste site does not necessarily mean that a person is highly exposed to its wastes – why?
3. Only potential risks to human beings are discussed in this chapter. When is risk important to the surrounding wildlife or ecosystem?

SECTION IV

Reducing the risk of hazardous-waste sites

You know that pollution prevention is the preferred step in the waste-management hierarchy. However, once a spill has occurred it is too late for P^2. Nonetheless, spills have pushed companies to pursue P^2. This has happened because of the cost, bother, and bad publicity that result from spills and hazardous-waste sites. It also has happened because companies, like society at large, have become more aware of the results of indiscriminate disposal that characterized earlier years.

Immediate protections afforded to those living near a site

Of 1300 NPL sites, the US EPA concluded that 2% posed an imminent hazard. An imminent (urgent) hazard is dealt with quickly to avoid continuing exposure to nearby communities and to protect workers. Examples of imminent hazards are explosives, or conditions that could lead to the site's chemicals contaminating groundwater used for drinking water. ■ Even if a site poses no imminent hazards, recommendations are often made to limit possible exposure to waste-site chemicals. Steps taken may include: providing a different source of drinking water; issuing fish-consumption advisories; or just restricting access to the site. Site clean-up is more tedious.

Cleaning up the site

Once the site characteristics are well understood, clean-up possibilities are considered. For an NPL site, the EPA consults with others to select a clean-up remedy from among identified alternatives. ■ The selected remedy must comply with federal, state, and local laws. It must also protect human health and the environment – but this is controversial: must the site be returned to "pristine" conditions? Or if it is to become an industrial site again or a parking lot, can the clean-up stop after 90% or 95% of the contaminants are removed (Box 12.3)? ■ After remedy selection, an engineering design is prepared followed by the construction necessary to accomplish the clean-up. Finally the remedy is carried out. All these actions may require 10 years or more and, after the clean-up, monitoring must continue for years. If groundwater is being treated, the process could take many more years yet. The EPA takes responsibility for the NPL sites, but others may perform the actual clean-up. The public has a right to comment at all stages, although some believe their input is not always taken seriously.

Clean-up is funded in two ways: ■ If parties responsible for creating the site are identified, they pay. ■ If parties cannot be identified or if the sites are old ones, such as abandoned mining areas or sites that manufactured town-gas (some from the nineteenth century), a "Superfund" pays for the clean-up. The Superfund was created by a tax levied on oil, chemical, and manufacturing industries. If the company

Box 12.3 How clean is clean?

There are a number of reasons why a business might not buy an abandoned industrial site, a "brownfield", to locate its facilities. One reason is that it may be required to clean up the purchased land. To avoid potential problems, a company purchases a "greenfield," i.e., undeveloped land. Inner-city Detroit is particularly devastated by large tracts of abandoned land, some said to resemble a war zone. So strict clean-up standards can inhibit land reuse and lead to the development of ever more land. To counter this trend, the EPA began funding pilot brownfield redevelopment projects. There is hope for *site-specific standards* that will allow a site to be cleaned up to a standard consistent with its future use. Other proposals for brownfield sites are to reintroduce vegetation, especially native flora. These could provide badly needed greenery and parks for urban areas.

actually responsible for creating the site now has different ownership, its new owners must take responsibility. This has led companies to be very careful about properties that they purchase. For example, Hooker Chemical Company disposed of hazardous waste at Love Canal, but Occidental Chemical, the subsequent owner had to assume most responsibility for its remediation. The clean-up of NPL sites has been slow, mostly because there are many legal challenges. Recently, the US Congress allowed the Superfund tax to expire. Now there is concern that some sites may not be cleaned up properly or may have to be cleaned up at public expense. The clean-up of many sites, such as those contaminated by the military and the Department of Energy, are already government funded.

Clean-up methods

You are already familiar with methods used to treat hazardous waste (Table 12.1). The techniques used to clean up hazardous waste at abandoned sites (see below), are similar, but more complex. Consider the complexity of cleaning up a Love Canal or the clean-up made necessary by finding dozens or hundreds of drums of leaking chemicals.

Cleaning up metal contamination

Soil contaminated with lead or other heavy metals is often found at hazardous-waste sites, and at old mining sites. ■ One way to deal with metal-contaminated sites is to *excavate the soil* and, after treatment, bury it elsewhere in a landfill dedicated to hazardous waste. This option is expensive, and simply moves the problem "away." ■ Another option is to *stabilize the metals on site* by heating the soil to a temperature high enough to melt the soil into a hard mass (vitrification). This is very expensive. A less-expensive on-site stabilization technique is mixing the soil with cement and letting it solidify. Stabilized metals are much less likely to leach (especially if vitrification is used). ■ The method used to *remove the metals from the soil* depends on the particular metals involved. One, the TERRAMET® process, removes lead from soil. As you read the following details, notice that lead is recovered for recycling. (1) Soil is separated into its components (gravel, sand, silt, and clay). (2) The *gravel*, after washing it to remove most of the lead, is returned to the site. (3) The *sand* is shaken in water. Because lead is denser than sand, it settles to the bottom and is removed. The sand itself is treated with a proprietary chemical that dissolves the remaining lead. Clean sand is returned to the site. The proprietary solution is treated to precipitate the lead, which is then recovered. (4) *Silt and clay* are treated by methods similar to those for sand, and are also returned to the site.

Bioremediation

Living organisms can sometimes be used to *bioremediate* hazardous-waste sites that are contaminated with oil or with munitions. They are sometimes used also to clean up contaminated water or sediments. The microorganisms and plants used must be ones that concentrate the contaminant of concern while, at the same time, not being poisoned by it.

Bioremediation using microorganisms

The waste site is investigated as to its pollutants, characteristics of its soil and water, and microorganisms that are naturally present. Often these microbes have already slowly begun to degrade organic waste. In such cases, humans may work to speed up the action of these microbes by adding nitrogen or other nutrients; or, aeration may be used for microbes that need oxygen. A well-known use of bioremediation followed the *Exxon Valdez* Alaskan oil spill: physical clean-up methods, such as using high-pressure water to wash oil from rocks, were not effective and may have been harmful. But bioremediation helped; microbes naturally present along the shore had already begun degrading the oil's hydrocarbons, and tidal flux was providing oxygen. A nitrogen fertilizer was added to speed microbial action. Microorganisms that received fertilizer degraded surface and subsurface oil three to five times faster than microbes in unfertilized areas. Oil that could have taken 10 years or longer to naturally degrade broke down in 2 to 3 years. Microbes could not degrade those hydrocarbons that had become immobilized into an insoluble asphalt-like material. However, the immobilized hydrocarbons were not expected to affect biological systems adversely.

Bioremediation at metal-contaminated sites

Microbes of course cannot destroy metals, but do sometimes convert them to less-hazardous forms. ■ They sometimes carry out reactions that lead to metal stabilization. At one site, microbes converted sulfate to sulfide. Sulfide in turn reacted with metal contaminants at the site to produce metal sulfides. Metal sulfides are very insoluble. The final effect was to immobilize the metals in place, analogous to stabilizing metals in soil by heat or cement. But the microbial treatment is cheaper and more environmentally benign. ■ In another case, microbes concentrated *plutonium*, a dangerous radioactive element present at a site. This is an ability that has promise to help clean hazardous-weapons-production sites.

Natural microbes are typically used in remediation projects, but effort is ongoing to bioengineer organisms that can degrade specific chemicals. A "bioengineered organism" is one into which one or more genes have been introduced to make it capable of carrying out a task it previously was unable to accomplish. Recently, bacteria capable of decomposing dioxins and PCBs have been developed. Although natural microbes can degrade PCBs and dioxins too, they do it very slowly. The challenge is to develop organisms that effect rapid destruction of hazardous chemicals, while not themselves becoming a new environmental risk.

Phytoremediation

Hundreds of plants and trees have been identified that can accumulate metals from soil or water, sometimes to high concentrations (*hyperaccumulate*), and can do so without ill-effects to themselves. Plants can hyperaccumulate many different metals such as nickel, zinc, copper, cadmium, selenium, and manganese. Certain plants hyperaccumulate metals up to 40% of their weight without harming themselves. Why they hyperaccumulate is unknown, but it may give the plants a metal taste, which insects, that otherwise would feed on them, do not like. Plants can subsequently be harvested and burned to recover the metals. One aquatic plant took water contaminated with the explosive 2, 4, 6-trinitrotoluene (TNT) from a concentration of 128 ppm down to 10 ppm. Also, envision a hazardous-waste site covered with attractive plants or trees that are cleaning it up. You can see the appeal of phytoremediation. However, phytoremediation is not yet widely practiced. It is believed that more successful demonstration projects are needed to ensure future commercial success.

Bioremediation's potential

Bioremediation, whether with microbes or plants, is still at an early development stage, but its potential is tremendous. It costs less than a technology such as excavating and incinerating contaminated soil. And, rather than using brute force it works with natural systems. Yet bioremediation raises a familiar problem – it cannot destroy or take up that last small amount of a contaminant. Microorganisms usually degrade a chemical because they use it as a nutrient or source of energy to promote their own growth. When the concentration of the chemical becomes low, it no longer supports microbial growth. When growth stops or slows, so does accelerated degradation of the chemical. Likewise, there is no biological reason for a plant to hyperaccumulate every bit of a metal in soil or water.

Box 12.4 | Think ambitiously

Bioremediation's potential goes far beyond treating hazardous-waste sites. Some countries already use microorganisms to treat industrial-waste effluents, both air and water. In Austria, the feasibility of using microbes to degrade the organic material in MSW is being explored. Success could make it unnecessary to landfill MSW. Japan is evaluating some very ambitious bioremediation projects. In one undertaking, researchers are studying a material produced by a bacteria that can absorb 1000 times its own weight in water. They envision using this absorbent to remediate the world's growing deserts. Japan is also considering projects using microbes to recover the greenhouse gas, carbon dioxide from power plant stacks, and to convert it into substances that will not enter the atmosphere. They also ask the ambitious question, could living organisms be modified to remove carbon dioxide from the atmosphere more effectively?

Questions 12.3

1. Organic hazardous wastes can be treated by spreading them on land and allowing natural processes to degrade them. (a) What natural factors contribute to such degradation? (b) What are the potential environmental health and safety shortcomings of land spreading?
2. Consider hazardous chemicals buried in water-body sediments. What natural factors, available above ground, are no longer there to assist in the degradation?
3. Bioremediation has great potential. Might it have potential risks? Explain.
4. Consider three methods used to remediate lead-contaminated soil: (1) soil excavation and removal; (2) Thermal stabilization; (3) The TERRAMET® process. (a) What are the environmental impacts of each? (b) Which do you believe is preferable and why?
5. CERCLA, or the Superfund law, resulted in more-responsible waste disposal. It also stimulated more P^2 efforts – how?

SECTION V

International transport of hazardous waste

Could it be considered a criminal act to ship thousands of tons of concrete waste from a more-prosperous nation into Cambodia, an impoverished nation, to have it disposed of there? In this case the waste was so contaminated with mercury that it caused deaths among local people and panicked many others to such an extent that they left their homes. Other wastes transported into less-developed countries include drums of hazardous waste (Figure 12.2). Another is medical wastes including hypodermic needles and used bandages concealed in containers marked "paper" (for recycling). These are a few examples of waste transported from prosperous to impoverished nations that lack

Figure 12.2 Children play among 5000 barrels of illegally dumped hazardous waste. Credit: Chris Albertyn, Durban, South Africa

an infrastructure to handle it safely, follow where it goes, or properly dispose of it. Waste is handled in a manner that the countries of origin wouldn't allow to occur on their own soil.

The Basel Convention

To address such problems, the United Nations passed a treaty, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. ■ Its objectives are to: (1) minimize hazardous-waste generation; (2) dispose of hazardous wastes close to where they are generated; and (3) reduce the international movement of hazardous wastes. The convention prohibits transboundary movements of hazardous or other wastes without *prior written notification* by the nation exporting the waste to authorities in the country that is importing it. Shipments must also be accompanied by appropriate documents. There are also outright bans on the export of hazardous wastes to certain countries. The Basel Convention is a global agreement ratified, as of April 2000, by 135 member countries and the European Union. The United States has not ratified the treaty, the only industrialized country not to do so.

Electronics waste

Discarded electronics is but one waste stream, but an ever-growing stream. They illustrate too what can happen when wastes are sent to poor nations who do not have the infrastructure to handle them – even a "non-hazardous" product can become so. Each year, US households and businesses buy about 57 million computers and televisions. These lack environmentally preferable characteristics (Box 11.2): they are not durable, are often less expensive to buy new than to repair the old, and are not economically recycled. And, as better and faster

Figure 12.3 Left, Chinese workers pick through wires torn from computers. Right, Woman prepares to smash a computer monitor cathode-ray tube to remove the copper-containing yoke. Credit: Basel Action Network

computers and other electronics are created, many prefer these even when repair is feasible. The electronics stream is growing rapidly – the US National Safety Council estimates that 315 million computers will have become obsolete by 2004. And computers are but one among many waste electronic products.

An ocean of electronic discards

Discarded electronics are difficult to disassemble. They became increasingly uneconomical to recycle because their valuable-metal content has been decreasing.[3] Silicon chips were previously gold backed, but no longer. Metal use in printed wiring boards has decreased too. Computer housing was once made of steel and was a valuable recyclable item, but the housing is plastic now. Only 11% of the US electronic discards in 1998 were recycled with most discarded computers, monitors, printers, and other US electronics going to landfills. Some states, including Massachusetts and California, have banned cathode-ray tubes (CRTs) from landfills. Several state governments subsidize electronic collection and recycling. Because this is expensive, they may lower costs by using prison labor. A few reputable recyclers exist, operating in an environmentally sound way, repairing newer electronics for reuse and recycling materials from the rest. However, private recyclers cannot compete with cheap prison labor. The result is that 50% to 80% of the waste electronics collected in the United States for recycling is shipped to China, India, or Pakistan (Figure 12.3). There it costs only 10% as much to process waste electronics as in the United States. Labor costs are very

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[3] Computers contain tiny amounts of valuable metals: cadmium, chromium, lead, beryllium, mercury, even tiny amounts of gold. These can be recovered, but not simply, and components contain too little of these metals to make recycling economical in industrialized countries. Electronics also contain brominated flame retardants, and billions of lbs of plastics. There is one good piece of pollution-prevention news: a computer or television cathode-ray tube (CRT) previously contained several lbs of lead, now three out of four manufacturers are manufacturing lead-free panels for CRTs.

low, safety and environmental regulations are ignored. Other countries that ship waste computers overseas include Canada, Japan, and South Korea. However, the European Union has ratified the Basel Convention, which forbids EU countries from making such shipments.

How to make a computer hazardous

In Asian countries, adults and children work under primitive conditions to break up electronics. Hundreds of people may work in one shed or outdoors, hammering apart computers to recover wires and other components. Workers lack ventilation or protective clothing, unprotected too from the smoke of open fires used to recover metals. Salvaged metals include copper from wires, bits of gold from computer capacitors, small amounts of mercury from batteries and switches, and a little beryllium from computer motherboards. Acid is used in some operations without worker protection to recover tiny amounts of gold from semiconductor chips. Plastic casings are burned, shredded for use in new low-quality products, or just dumped along with other trash and ash. Runoff carries contaminants into local rivers and into rice paddies. Lead and other metals in the river running through Guiya, a Chinese town, are found at levels many times greater than WHO standards (Figure 12.3). The river is black with pollution and also contains strips of plastic and shards of glass. Fish kills occur and drinking water must be trucked into a town such as Guiya. Guiya is littered throughout with piles of motherboards, hard drives and keyboards, and glass from monitors. Nonetheless, workers want these jobs although they admitted to *Washington Post* reporter, Peter Goodman, that they had problems such as finger cuts that did not heal, and hacking coughs resulting from lack of ventilation. Some children work full-time, and air pollution affects those remaining in school. China has banned electronics imports, but importers bribe customs officers to continue the trade. China has requested that the United States and other countries discontinue shipping electronic waste because otherwise, even if China successfully stops the imports, wastes will just go to Vietnam or the Philippines. Indeed, this has already started.

Reducing electronics exports

Action in Europe

As signatories to the Basel Convention, 135 countries plus the European Union ban hazardous-waste shipments except under carefully defined conditions. Other actions are under way too: ■ One is a recyclers' pledge developed by the Basel Action Network. Companies signing the pledge declare that they will not send discarded electronic products to a landfill or incinerator, or to a developing country for disposal. ■ The European Union has taken another action. It passed a Waste Electrical and Electronic Equipment Directive. Starting in 2005, manufacturers must take full responsibility for discarded electronic products. This *take-back* or *extended producer responsibility* (EPR) program means that manufacturers are responsible for recycling. For 10 years, they will be able to charge consumers a recycling fee. The fee will pay for recycling older electronics manufactured before the law was passed. The directive's purpose is to promote recycling and reuse of electrical and electronic products. The directive also asks manufacturers to phase out lead and certain other hazardous substances in electronics. Japan is taking similar actions.

United States

Environmental organizations in the United States want a European-type solution of mandatory take-backs. They ask too that a system be set up to collect used electronics, and that methods to ensure environmentally sound recycling are developed. ■ The US electronics industry is fighting mandates on EPR. Instead it advocates shared financial responsibility with government and consumers. Consumers could share responsibility by paying a fee when buying electronic equipment. The fee would assure money for recycling, at least until design for the environment (Dfe) efforts result in designs that, allow electronic recycling to pay its own way. ■ Panasonic has taken several steps in the direction of design-for-disassembly, design-for-recycling. To make plastic recycling more feasible, it cut the number of plastic types in its television sets from 13 to 2, labeling each to allow more convenient separation during disassembly and recycling. It also reduced the number of plastic parts in its televisions from 39 to 13. Very importantly, Panasonic cut the time required to disassemble its televisions from 142 to 78 seconds. Panasonic also uses 10% recycled glass in its CRTs (the funnel-shaped glass in monitors) and plans to introduce televisions with lead-free solder.

Several US companies have started what one article called "baby steps to electronic waste take-back." Under limited circumstances dealers will, for a fee, accept used electronics (televisions, computer monitors, printers, central processing units, video-cassette recorders, telephones, cellular phones, and camcorders). ■ Panasonic, with other manufacturers and dealers, initiated an Electronics Product Stewardship Initiative. Its goal is to find end-of-life solutions for discarded electronics. The initiative's intention is to create a voluntary take-back program for electronics. ■ Sony has a six-state program in which it will take back all its electronic products, including computer monitors and televisions, for recycling. ■ The EPA urges manufacturers to view "waste" electronics as a raw material source and to use "design for the environment" to begin to move toward less or even zero waste.

Questions 12.4

1. Consider electronic waste. From your perspective, what would be an ideal way to deal with the problem of electronic waste?
2. You have been introduced to "design for the environment" (DfE). Give several examples of European or American actions that use DfE.
3. What are the ethical responsibilities of: (a) Manufacturers of consumer electronics? (b) Governments? (c) Individuals such as yourself?

Reducing hazardous-waste generation

The goal of several actions described above is to reduce hazardous-waste generation. The Basel Convention aims not just to manage hazardous waste responsibly, but to minimize its generation. Some steps taken in Europe, and a few in the United States, specifically push P^2, DfE, or industrial symbiosis. ■ Although much space is devoted here to electronics waste, it is but one waste that can be dangerous. Many other hazardous wastes exist. These include contaminated liquid organic solvents, and aqueous waste streams contaminated with metals. ■ One approach being used to minimize chemical hazardous waste is green chemistry, DfE specifically directed toward chemicals. Green chemistry works to design chemicals and processes that use and produce more environmentally benign chemicals, and produce less hazardous waste (see Chapter 18).

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Chapter 13

Energy

“The world is not running out of energy. But it is running out of environment, patience with inequity, money for sustainability, time for making a transition to more sustainable energy options, and leadership to do what is required.”

Dr. John Holdren, Harvard University

You saw in earlier chapters the major ways that energy use leads to ambient air pollution, and to acid deposition and global climate change. You also saw its contribution to the nitrogen glut and other water and soil pollution problems. This chapter looks specifically at energy production and use, and alternatives to fossil fuels. **Section I** surveys world energy use past, present, and future. Overviewed in **Section II** is our great attachment to motor vehicles, the results of that fondness, and how we can reduce some adverse impacts of motor vehicles. **Section III** examines another major user of energy, electricity generation, and some of the many approaches for reducing the pollution associated with it. **Section IV** brings us to an examination of alternative fuels. **Section V** briefly surveys energy use in less-developed countries, while **Section VI** summarizes sustainable energy generation.

SECTION I

Overviewing world energy use

World energy use is increasing steadily (Figure 13.1). Between 1970 and 1997 consumption nearly doubled. It is projected to rise another 60% between 1997 and 2020. Emissions of carbon dioxide and other pollutants rise in step with energy consumption. Energy use is projected to grow with special rapidity – by 120% – in developing

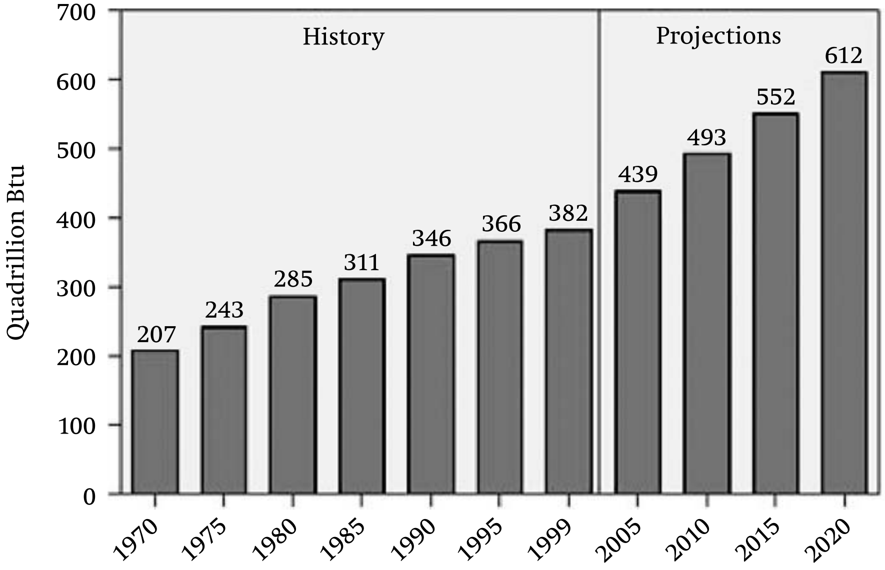

Figure 13.1 Increase in world energy consumption (1970 to 2020). Source: US DOE/Energy Information Administration (EIA)

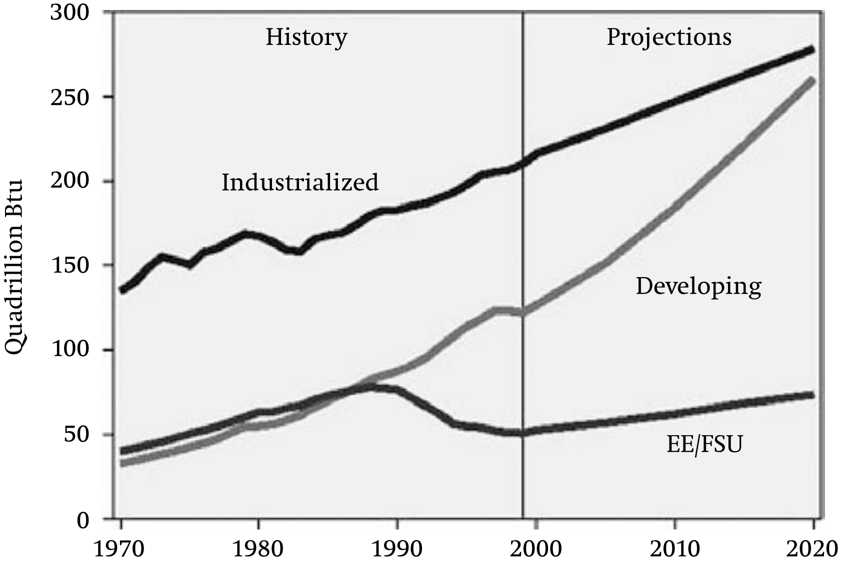

Figure 13.2 Increasing energy use by part of the world (1970 to 2020). EE/FSU, Eastern Europe/former Soviet Union countries. Source: US DOE/EIA

countries (Figure 13.2). Consumption would be higher still except, fortunately *energy intensity* is rising too. Energy intensity is the amount of energy used per dollar of gross domestic product. The United States uses about one-quarter of the world's energy, about three times more per capita than a Japanese citizen, and ten times more than many

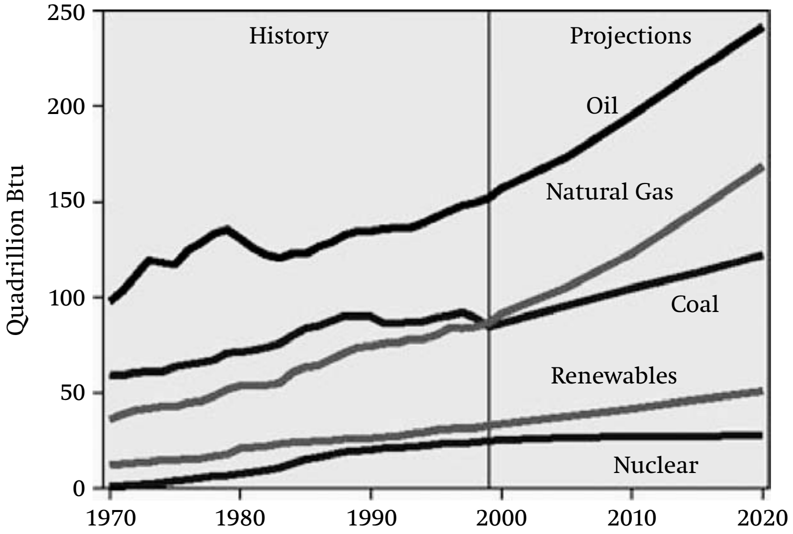

Figure 13.3 Types of fuels burned around the world (1970 to 2020). Source: US DOE/EIA

in poorer nations. Ninety per cent of the world's energy is obtained from fossil fuels (Figure 13.3); in the United States in 2000, that figure was 82%. Commenting on our fossil-fuel dependence, Kurt Yeager of the US Electric Power Institute said, "To a large extent, we're still operating with a hunter–gatherer mentality." The planet has abundant coal that will last for centuries, but experts differ on how close we are to having used half the world's oil. Opinions range from a few years to several decades. After half the oil is used, oil prices are expected to rise rapidly. Other sources of oil, such as oil shale, are more expensive and more environmentally disruptive to access and process.

Half the world's population cannot buy fossil fuels at all, or else buy very small amounts. These very-poor individuals do not contribute to fossil-fuel problems. They rely, as did their and *our* ancestors, on wood if available. Indeed, over 60% of the wood consumed in the world is used as fuel. Other fuels used by these 3 billion people are agricultural wastes and dung. In China, the people burn coal, but that poor-quality coal is responsible for human poisonings and environmental ills.

Coal-mining and oil-recovery operations can have ruinous effects on local environments. When burned, they pollute, sometimes heavily. Table 13.1 reviews the major impacts of pollutants emitted when fossil fuels are burned: global climate change, acid deposition, ambient air pollution, and eutrophication. Continued fossil-fuel burning raises the question, how much more pollution can our environment absorb? Despite all these problems, when projections are made to the year 2020, it appears that no more than 6% of the energy used within the world's most prosperous nations (the 29 nations comprising the Organization for Economic Cooperation and Development, OECD) will come from renewable sources such as solar or wind.

Table 13.1 Review of air pollutants resulting from fossil fuels

	Fossil fuel responsible[a] for effect noted
Global climate change	
Carbon dioxide (CO_2)	Coal burning produces more carbon dioxide than petroleum, which produces more than natural gas.
Methane	Methane primarily arises from coal and petroleum recovery and natural-gas pipeline leaks.
Acid deposition	
Sulfuric acid and sulfate	Sulfuric acid and sulfate form in the atmosphere from SO_2.
Nitric acid and nitrate	Nitric acid and nitrate form in the atmosphere from NO_x.
Ambient air	
Sulfur dioxide (SO_2)	SO_2 is emitted in especially high amounts by coal-burning facilities, and to lesser extents by burning oil and natural gas.
Nitrogen oxides ($NO_{x)}$	NO_x forms from a reaction between nitrogen and oxygen during high-temperature combustion. In urban areas motor vehicles are the major source. Power plants are also important.
Carbon monoxide (CO)	CO is a product of incomplete combustion (due to lack of oxygen). In urban areas, up to 90% is from gasoline combustion.
Ozone (O_3)	O_3 is not emitted as O_3, but forms from other pollutants. Motor vehicles are the major source of NO_x and VOCs, which lead to O_3.
Particulates	Coal burning is a source of particulates; so is oil burning. • Metals are emitted as particulates (excepting elemental mercury).[b] • The particulate, carbon soot, results from incomplete combustion.
VOCs	
• Hydrocarbons	Hydrocarbons are the major volatile organic compounds (VOCs) emitted from gasoline-burning vehicles.
• PAHs	Some PAHs are volatile.[c]
Eutrophication	
Nitrogen oxides (NO_x)	Fertilizer is the source of "fixed nitrogen," but motor vehicles contribute increasing amounts.

[a] Fossil-fuel burning is not the only source of many of these pollutants, but it is a major source.

[b] Coal and oil have only trace amounts of metals. However, because metals are persistent, levels can build up in the environment if burning continues and if emissions are not well controlled.

[c] Unlike the bulk of hydrocarbons (which are linear chemicals), PAHs are "polycyclic" aromatic hydrocarbons. PAHs are incomplete combustion products from burning coal, oil, or other carbon-containing fuels. Heavier PAHs are not VOCs, but are found in soot.

SECTION II

Motor vehicles

Transportation problems have been with us for thousands of years. In ancient Rome, chariots were banned during the busiest parts of the day – they caused traffic jams. Coming far ahead to the New York City of 1900 we learn that horses deposited several million lbs of droppings each day, filled the air with pungent urine fumes, and dried droppings entered the air as pathogen-carrying dust. Under those circumstances, motor vehicles seemed to offer a public-health benefit: as cars displaced horses tuberculosis rates fell dramatically. Today we depend almost entirely on gasoline-powered motor vehicles, and now it is those vehicles that pose great problems. In 1990, US motor vehicles emitted 65% of the country's carbon monoxide (CO), 33% of the nitrogen oxides (NO_x), and 29% of the volatile organic chemicals (VOCs). They also emit soot-containing particulates, polycyclic aromatic hydrocarbons (PAHs), and metals (Table 13.1). Percentages emitted by motor vehicles are higher in urban areas: in the San Francisco of 1990, cars emitted 75% of the city's carbon monoxide, 58% of nitrogen oxides, and 38% of VOCs. It is due to vehicle pollution that many US cities are out of compliance with federal air quality standards, most often in the summer months. In the United States, automobiles also generate about 25% of the greenhouse gas, carbon dioxide (CO_2). In fact, an average vehicle produces its own weight in carbon each year.

Pollutants and problems

Look at US and Canadian cars. Over half sold today are not cars, but sports utility vehicles (SUVs), minivans, and light trucks. About one-third of the vehicles are larger than even the behemoths of the 1950s. Today's US motor-vehicle fleet averages 20.8 miles per gallon (mpg) or 8.84 km/l, about 6% lower than the high point attained in 1988 – and that was only 22.1 mpg (9.4 km/l). Many more cars are sold today than at any previous time with car ownership growing six times faster than the population. And each of these cars travels more miles than did cars of earlier years. Not surprisingly, a UN study showed that US and Canadian citizens use nine times more gasoline than the global average. All forms of transport put together, cars included, consume about one-third of the energy used in the United States – and that proportion is growing. Roads continue to be built to "solve" the congestion created by many millions of vehicles. Roads add to the burden of impervious surfaces, to local water and air pollution, and to disruption of wildlife habitat. And adding roads doesn't solve congestion. University of California Professor M. Wachs notes, "You can never build enough roads to keep up with congestion. Traffic always rises to exceed capacity."

Many European cities have population densities four times greater than American cities. Shopping and other facilities are close enough to homes that individuals can make up to 50% of their trips on foot or bike. And about 10% use energy-efficient public transport. Trains, e.g., are per passenger six times more energy efficient than cars. In contrast, US individuals make 87% of their trips by car and only 3% via public transport, although that percentage is slowly growing. Author Molly Sheehan[1] states, "US drivers consume roughly 43% of the world's gasoline to propel less than 5% of the world's population." In the early twenty-first century, 56% of the petroleum used in the United States must be imported, a percentage that steadily continues to rise. Motor vehicles use more oil than the United States produces – the United States has only 2% of the world's reasonably accessible oil reserves. If Americans burned less gasoline, they could import less petroleum. Not only does burning gasoline exert a heavy environmental price, dependence on foreign oil threatens national energy security. Nonetheless, gasoline use continues to grow. Citizens do not demand change, and politicians in the United States and Canada lack the will to change the situation.

Mark Hertsgaard in his book, *Earth Odyssey*[2] says, "The automobile may well be the ultimate symbol of the modern environmental crisis." Together the Earth's half a billion cars use one-third of its oil, and emit one-quarter of its carbon dioxide. Cars are also resource intensive to build. In 1995, the average car used nearly 1800 lbs (816 kg) of steel, 398 lbs (180 kg) of iron, 188 lbs (85 kg) of aluminum, and 246 lbs (112 kg) of plastics. Now, as Americans buy even larger vehicles, resource use is higher still. A vehicle can produce as much pollution during its manufacture as over a lifetime of driving. "In what must rank among the great corporate crimes of the century, General Motors secretly joined with Standard Oil of California, Firestone Tire and Rubber, Phillips Petroleum, and Mack (Truck) Manufacturing in 1932 to form National City Lines" This syndicate bought about 100 railways and trolley lines in 45 US cities, shut them down and tore out their tracks. Their "punishment" was a $5000 fine in 1949. Over this time highways were being built, and it was to private cars and "freeways" – exactly as the co-conspirators desired – that Americans turned.

Box 13.1 | A world enamored of cars

It is not just North Americans that love cars. As what Hertsgaard calls, "The Irresistible automobile," the car remains the ultimate status symbol. Worldwide, car ownership grows three times faster than the population. ■ The United States exports used cars to Central America where they sell well because they are much cheaper than new cars. But older cars often have poor fuel efficiency and pollution control. They are major contributors to high levels of carbon monoxide and other air pollutants. Environmentalist Marco Gonzalez of El Salvador said,

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[1] Sheehan, M. O. *City Limits: Putting the Brakes on Sprawl*. Worldwatch Paper 156. Washington, DC: Worldwatch Institute, 2001.

[2] Hertsgaard, M. *Earth Odyssey: Around the World in Search of our Environmental Future*. New York: Broadway Books, 1999.

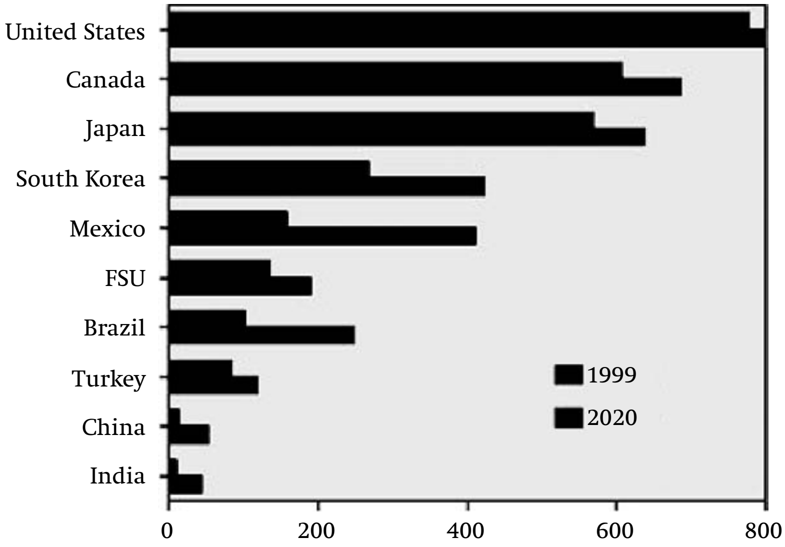

Figure 13.4 Number of motor vehicles per 1000 population. The top bar for each country is for 1999, and the lower bar is a projection to 2020. FSU, countries of the former Soviet Union. Source: US DOE/EIA

"Central America has become a junkyard for cars from the United States." ■ More generally, developing countries drive older cars and trucks lacking modern pollution controls. ■ Mark Hertsgaard describes the situation in Bangkok, Thailand. This city has almost no public transport. Motor-vehicle pollution on and near roadways is difficult to bear for those unaccustomed to it. Massive traffic jams regularly slow traffic almost to a standstill, leading some people to take toilet facilities with them. ■ Public transport and bicycles are still heavily used in China with only about one person in 85 owning a car. Nonetheless, those that are in use produce what observers describe as staggering congestion. They also already produce up to 60% of the nitrogen oxides in Chinese cities and 85% of their carbon monoxide. China needs to maintain its agricultural land to feed its huge population, but also needs highways to connect its cities. Yet China intends to increase vehicle ownership.

The world now has about a half a billion cars, a figure moving toward one billion by 2020 (Figure 13.4) Manufacturing and fueling cars is now the world's biggest industry. As with brooms multiplying in the story of the Sorcerer's apprentice, motor vehicles too seem to multiply out of control. And beyond cars we of course manufacture many other motor vehicles – trucks, farm machinery, snowmobiles, all-terrain vehicles, and gasoline-driven appliances of all types including lawnmowers and leaf blowers. The problems seem almost insoluble. Yet that situation may be, albeit very slowly changing.

Reducing the damage caused by motor vehicles

Hertsgaard speaks of, "domesticating the car." He and others recommend mandating that cars have greater fuel efficiency and use less-polluting fuels. Other recommendations are to raise the fees charged on cars, and aggressively promote carpooling. With 200 million motor vehicles in the United States alone – a number that is growing – the problem is immense. Reducing or eliminating vehicle emissions is discussed below. As you read, remember that, in addition to reducing emissions, other problems that cars pose also need addressing. Even if vehicles emitted zero pollution the environmental and other problems that our vehicles cause would not end. Cars destroy many communities as high-speed–high-traffic roads bisect them, and as people increasingly move to suburbs using the new roads. Human development sprawls to ever-further-out suburbs with ever-increasing distances driven to reach them. In addition to pollution – to air from increased driving, to water from increased runoff of oil, tire shreds, and the like – there is increased disruption of wildlife habitat, and farmland destruction.[3]

Box 13.2 | A conundrum

A National Research Council (NRC) panel examined the US car fleet. They determined that improvements – that did *not* involve changing vehicle size or decreased performance – could increase fuel economy by 55%. Manufacturing costs, although higher would be offset by fuel savings over the vehicle's life. But, they concluded that more and bigger vehicles would cancel out increased fuel efficiency. Indeed, by 2003, the fuel economy of the average US vehicle was less that than in 1989.

The US Clean Air Act

The 1990 US Clean Air Act Amendments (CAAA) mandated steps to reduce motor-vehicle pollution from cars, buses and trucks, non-road vehicles, boats, farm equipment, bulldozers, lawn and garden devices, and construction machinery. ■ Tailpipe emissions were tightened. Cities not in compliance with EPA standards were expected to reduce hydrocarbon emissions by 25% to 29%, toxic emissions by 20% to 22%, and nitrogen oxide emissions by 9% to 10%. Many approaches were used to accomplish this.

Conservation

Conservation is the ideal. The CAAA asked the smoggiest cities to limit growth in vehicle travel by encouraging alternatives to people driving alone in cars. In especially polluted areas, employers of 100 or more people were asked to find ways to increase the number of passengers in each vehicle commuting to work and in work-related driving trips. Ways to do this include encouraging people to carpool and providing incentives to carpool. Providing bike paths to encourage biking is also useful combined with a place to shower for bikers when

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[3] An evaluation by the US Union of Concerned Scientists concluded that, of all our personal habits, it is transportation, driving cars in particular, that is most environmentally destructive. Moreover, about 40 000 people die in accidents each year in the United States Worldwide, about 900 000 a year die. And the gasoline our vehicles use has an impact upon national energy security. Many recommend the re-urbanization of America; that is, that we move back into more compact communities. This would benefit public transport, and increase the number of people walking and biking to get groceries and other necessities. Professor Tim Gutowski of Massachusetts Institute of Technology notes that the automobile even threatens itself. This is true because infrastructure and roadway construction cannot keep pace with ever-increasing vehicle use especially in locales where population densities are already high. He believes this point has caught the attention of some automobile companies.

they get to work. Most important in the long run is to redesign cities in ways that make walking, bicycling, and use of public transport convenient.

Reducing carbon monoxide emissions

Motor vehicles are the major source of carbon monoxide (CO) emissions in the United States. Two Clean Air Act programs addressed this problem. ■ Manufacturers were to modify vehicles to lower cold-engine emissions, which can represent up to 75% of the emissions on short trips. (Greater CO emissions occur in cold weather when fuel burns less efficiently and pollution-control equipment works less well.) ■ Remember that CO is a product of *in*complete combustion – more oxygen can assist in converting more CO to carbon dioxide and lead to reduced CO in the exhaust. It was logical then for the EPA to ask cities that were out of compliance with CO standards to use gasoline to which an oxygen-containing chemical was added.

Reducing ozone formation

The EPA characterizes ozone as the country's most serious and persistent air quality problem. Thus, EPA mandates placed tighter restrictions on emissions of hydrocarbons and NO_x, the pollutants that lead to ozone formation. One EPA program led to reduced hydrocarbon evaporation from gasoline; that evaporation had been a major hydrocarbon source. To accomplish this, manufacturers added devices to trap gasoline vapors from the engine and fuel system, and a trap to reduce the vapor emissions that humans are exposed to during refueling. Another means that the EPA used to lower hydrocarbon evaporation was to require that reformulated gasoline include hydrocarbons with a lower propensity to evaporate. ■ Chemicals furnishing oxygen. In the United States the chemical, methyl tertiary butyl ether (MTBE) was widely used to provide oxygen. However, MTBE proved more water soluble than expected; it became a widespread water contaminant and is now being phased out. The oxygen-containing chemical, ethanol (common alcohol) is touted as a replacement for MTBE although other oxygenated chemicals are available too. Ethanol is favored by mid-western US states that grow large quantities of corn, which can be used as the ethanol source.

Inspection and maintenance

About 10% of motor vehicles lead to 50% of all car emissions in the United States. This 10% includes old vehicles, but also improperly maintained vehicles of all ages. Some locales that are out of compliance with the federal ozone standard must have inspection/maintenance programs to identify offending vehicles. Owners must repair, or take off the road, vehicles that emit VOCs and nitrogen oxides at above standard levels. On occasion, a company will pay to repair cars that fail the test or to buy and scrap the vehicles. Sunoco did this in Philadelphia to achieve a partial offset against its own increased emissions when it expanded its refineries.

Alternative fuels

The Clean Air Act did not address *flexibly fueled vehicles* (FFVs). An FFV uses, not gasoline, but entirely different and less-polluting fuels including natural gas, propane, electricity, and biodiesel (commonly processed from used restaurant vegetable oil of which billions of gallons are available). Hydrogen is also of much interest. ■ Propane fuels hundreds of thousands of US vehicles, but that is only a tiny percentage of those on the road. Vehicle maintenance costs and engine wear are lowered because the clean-burning propane leaves no lead, varnish, or carbon deposits. Such vehicles emit lower amounts of ambient air pollutants. And because propane and natural gas contain less carbon than gasoline, vehicles burning them have reduced emissions of the greenhouse gas, carbon dioxide. ■ A major advantage to consumers of gasoline-powered cars is that an infrastructure is in place to service them: fueling stations, mechanics, etc. If a vehicle using a different fuel is to succeed, an infrastructure must be available to sell it and service vehicles using it. To encourage infrastructure development, the US Energy Policy Act of 1992 required that 75% of the “light-duty” fleet of federal agencies be FFVs. However, compliance has been inconsistent. Some local and state governments, and private companies, have bought a limited number of propane-fueled and hydrogen-fueled buses for use in some cities. ■ An important FFV using hydrogen fuel cells is discussed below.

Modifying vehicles for better fuel economy

European cars already have better fuel economy than North American ones. Recently issued directives will increase their efficiency another 40%. Japan too has passenger cars that get more than 40 mpg (17 km/l) of gasoline, as well as some ultra-efficient cars getting over 60 mpg (25.5 km/l) on the highway. However, US manufacturers and some unions resist mandates to produce cars with better fuel economy. Over half of American consumers now buy large vehicles, disregarding their poor fuel economy which can be as little as 10 or 12 mpg. One reason that Americans casually drive large vehicles is the low price of gasoline (Table 13.2). Nonetheless, if a 30 mpg sports utility vehicle was available that maintained high performance consumers could be expected to buy it. The US Congress has not changed national fuel economy standards since the mid-1970s. Many consider this astonishing considering that in 2001 the United States used, on average, 19.6 million barrels of oil per day, of which about 57% is imported, and despite fears of instability in oil-rich Middle-Eastern countries.

Low-emission and zero-emission vehicles

California, with its severe air pollution problems, requires that a small percentage of cars sold there have emissions reduced by 90%. A number of northeastern US states also want to sell low-emission vehicles, but the US EPA prefers to work toward national standards. ■ Honda introduced the first low-emission vehicle in the United States, a modified Accord EX engine with emissions reduced by 90%,

Table 13.2 | Gasoline Prices Around the World

Country	Price ($/gallon)	Price ($/liter)
United Kingdom	4.28	1.13
Japan	3.87	1.02
France	3.64	0.96
Brazil	3.49	0.92
Spain	2.77	0.73
India	2.27	0.60
Canada	1.90	0.50
United States	1.55	0.41
Russia	1.25	0.33

Data from: Sheehan, M. O. City Limits: Putting the Brakes on Sprawl. Worldwatch Paper 156. Washington, DC: Worldwatch Institute, 2001. Prices were those in autumn, 2000.

as compared with 1994. ■ In 2001, two special low-emission vehicles entered the US market, the Honda Insight and the Toyota Prius. These are powered by hybrid electric–gasoline engines. Unlike pure-electric vehicles, their driving range is not limited and their batteries (lightweight nickel–metal hydride packs) need not be plugged into a power socket to recharge. Batteries charge via regenerative braking; that is, the electric motor harnesses kinetic energy from the forward momentum of the vehicle whenever the car decelerates. Hybrid bodies and frames are made of lightweight materials designed to keep drag low. Depending on whether driven in town or on the highway, they obtain 50 to more than 60 mpg (25.5 km/l). Emissions are much lower than purely gasoline-powered cars, yet they are served by the gasoline infrastructure already in place. ■ Other types of hybrid vehicles also exist such as the buses in Denver, Colorado that use electric batteries charged by natural gas from a tank maintained on board.

Another small percentage of cars sold in California must be *zero emission vehicles* (ZEVs). A ZEV emits no VOCs, nitrogen oxides, or carbon monoxide. ■ ZEVs are often considered synonymous with electric vehicles (EVs). An EV doesn't pollute directly, but the electric power plant fueling it does. Even so, EV proponents argue that we control emissions from a limited number of electric power plants more efficiently than emissions from millions of individual vehicles, and power plants are usually found outside the most polluted urban areas thus relieving urban pollution. But an EV can be driven only about 100 miles (161 km) before plugging into a power socket for a long recharging. Lead-acid battery packs weighing about 1100 lbs (499 kg) make the vehicles very heavy (although a search for more practical batteries continues). Mining and smelting of metals going into batteries, and the manufacturing and recycling of batteries also generate pollution. Currently, EVs have market niches such as bus or tram systems. London uses electric trams as a means to lower the city's air pollution. ■ Another ZEV of great interest is the hydrogen fuel-cell-powered vehicle, which emits little more than hot water. Its engine makes little noise, and has low maintenance costs.[4] ■ Solar-powered vehicles are ZEVs too. ZEVs are commonly used now for competitions and demonstration purposes; for example, a group of Japanese engineers drove a car mounted with solar cells for 11 200 miles (18 000 km); the cells provided 10% of the power. There are prototype vehicles with higher percentages of their power furnished by solar energy.

Government action

Tokyo's municipal government is developing an eco-efficient ranking for cars, and plans to base automobile taxes on the car's ranking. This method is a push to manufacturers to design low-emitting cars with a high eco-efficiency ranking. Other governments are also examining ways to tax cars that depend on environmental performance; or, government fleets are sometimes asked to use less-polluting fuels, such as biodiesel, with the intention of setting an example that helps to start the process. A number of cities in the United States and elsewhere are using bus fleets fueled by alternative fuels.

Questions 13.1

1. (a) The United States consumes 25% of the world's petroleum, but has only about 2 to 3% of the reasonably recoverable world's oil reserves. Is the United States likely to find enough petroleum within its borders to increase production more than 12-fold? Explain. (b) What steps could the United States take to remedy this situation in the short run? (c) In the longer run?
2. Fuel-economy measures for motor vehicles focus on manufacturers. The US Office of Technology Assessment stressed that to reduce energy use and traffic congestion we must focus on how *individuals* buy and use motor vehicles. (a) What steps would you take to raise the consciousness of hundreds of millions of individuals on this issue? (b) What should be the balance between manufacturer and individual responsibility? (c) What changes would you be willing to make in how you buy and use motor vehicles? (d) Under what circumstances might you voluntarily give up your vehicle?

Box 13.3 | "Hydrogen is the fuel of the future and it always will be."

This statement represents the skepticism of some individuals about hydrogen fuel. Before we examine hydrogen, look at the Partnership for a New Generation of Vehicles (PNGV), which was a $1.5-billion-per-year shared effort between the US government and the automobile industry. Its goals were to triple vehicle fuel economy while maintaining safety. By 2001, PNGV had not produced marketable

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[4] A great barrier to fuel-cell cars is that, even assuming their price falls to affordable levels, an infrastructure must be developed that is different to the one devoted to gasoline vehicles. The exception is when hydrogen is "reformed" on-board from gasoline. However, this continues fossil-fuel use.

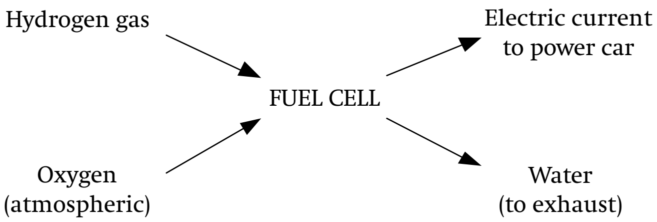

Figure 13.5 Hydrogen reacts with oxygen in a fuel cell to produce electric power

vehicles. It did have prototypes getting up to 70 mpg, lighter-weight vehicles with sleek designs exhibiting less drag when driven. In 2001, a new Washington administration cancelled the PNGV. It instead initiated work to mass-produce a "freedom car" powered by a hydrogen fuel cell and to assess establishing an infrastructure for such a vehicle. A *fuel cell* converts chemical energy directly to electric current (Figure 13.5).

Major problems must be solved if hydrogen-fuel-cell cars are to be practical and affordable. Presently, methane or gasoline is reformed at high temperature to yield the gas, hydrogen (although some fuel cells use methanol directly without reforming). How can hydrogen be generated cheaply and sustainably? How can hydrogen, an explosive and flammable gas that must be stored in pressurized tanks, be used safely? (But recall that gasoline and natural gas are also hazardous.) How will a very expensive infrastructure be developed to fuel and care for the vehicles? The hydrogen-powered car seems an ideal non-polluter emitting only water. But remember to look at the whole life of a product: obtaining the resources to make it, manufacturing it, using and maintaining it, and dealing with it end-of-life. Look at the generation of hydrogen fuel. Hydrogen is now made from natural gas; that is, it uses a fossil fuel, the very fuel we want to avoid. If hydrogen is to be a renewable fuel it must be inexpensive, be made sustainably, and be made in a way that emits little or no pollution; i.e., we need to produce hydrogen using a renewable fuel such as solar power. Critics say that the "hydrogen fuel cell just shifts pollution from vehicles to the hydrogen manufacturing facility," or to an on-board reformer using a fossil fuel. Supporters stress a belief that fossil fuels will be used only during a transitional phase.

The only way to start is to take the first steps although major problems remain. In late 2002, Toyota began leasing hybrid fuel-cell sports utility vehicles (SUVs) to facilities in California and Japan that have access to hydrogen. The vehicles use compressed hydrogen and, like other hybrids, they generate electricity through braking mechanisms. Toyota plans to assess vehicle performance, and hopes also to stimulate an infrastructure for fuel-cell cars. In a different approach, ExxonMobil and General Motors (GM) designed an on-board processor to generate hydrogen from gasoline, which would allow continued use of the gasoline station infrastructure for now. GM is also building a large research facility to determine how to mass-produce fuel-cell vehicles. One official said, "We're creating an industry that doesn't exist." GM expects to have fuel-cell cars on the market by the end of the decade. Moreover, the company hopes to produce other hydrogen-fueled products such as lawnmowers and farm equipment.

The goal is to generate hydrogen from renewable sources such as solar, wind, or biomass energy (i.e., electrolyzing water using renewable energy to yield hydrogen and oxygen). By the time we have exhausted petroleum or it becomes prohibitively expensive, hydrogen may come into its own.

SECTION III

Pollution from electricity production and use

We use electricity for a multitude of purposes including home and commercial lighting, heating and cooling, household appliances, and many industrial needs. ■ Electric lighting consumes about 25% of US electricity. An average household uses 1500 kilowatt hours per year (kW h/year) for lighting, 40% more than in 1970. ■ Electronic applications use increasing amounts of electricity. Office computers and related equipment use up to 20% of US electric power so office equipment continually left on is a major electricity consumer. ■ In industry, motors use about 50% of the electric power produced in the United States, and about 75% of all industrial electricity. Overall, the manufacturing sector consumes about 80% of the energy used by all industrial sectors combined.

Generating electric power

Worldwide, 90% of the energy powering the turbines that produce electricity comes from burning fossil fuels, i.e., coal, oil, and natural gas. ■ Coal, which is abundant and cheap compared with oil and natural gas, provides over 50% of US electricity. Looking at the picture worldwide, electricity consumption may grow an additional 76% by 2020, as compared with 1997 levels. This is especially likely to happen in Asia where coal already provides 80% of energy, and also in Central and South America. But is coal really cheap? The market price of a product doesn't take into account its environmental impacts, so-called "externalities." Add the externalities and coal could become an expensive fuel. ■ Nuclear power generates about 18% of the electricity worldwide, and about 11% of the needs of the 29 countries that comprise the Organization for Economic Cooperation and Development (OECD). In the United States and France (both OECD members) the figures are 15% and 80%, respectively. ■ Small amounts of electricity are also produced from burning biomass or municipal solid waste. However, the demand for fossil fuels continues to increase.

Fossil-fuel electricity

Coal

Before the industrial age wood was a common fuel. As wood became scarce in many locales in the eighteenth century, coal began what was eventually a 500-fold increase in use as Western economies industrialized. *Western civilization was built on the energy of coal*, the dirtiest fossil fuel. Coal remains so plentiful that it will probably continue to be used for many years. First, let's review the pollution and environmental degradation caused by coal mining, refining, burning, and ash disposal.

- Air pollution. Air pollutants directly affect us and the environment. They then affect us again after eventually being deposited onto soil and water. ■ The sulfur content of coal ranges from 1% to 5%. Industrialized countries often remove the water-soluble inorganic sulfur from high-sulfur coal before burning it. The organic sulfur remaining in the coal is part of the coal's matrix and is insoluble. Sulfur is converted to sulfur dioxide (SO_2) during burning, a major precursor of acid deposition. Modern equipment can capture almost all SO_2, but many facilities lack good controls. ■ The second major precursor of acid deposition, NO_x, also results from burning coal. Low-NO_x burners when installed can remove most. ■ Coal has only trace amounts of metals, but massive amounts of coal are burned, a billion tons (907 million tonnes) a year in the United States alone. Because metals are persistent, environmental levels can build up over time unless good controls are installed. Coal also contains radioactive elements, uranium (averaging 1.3 ppm) and thorium (averaging 3.2 ppm). People living near coal-burning power plants have higher exposure to radiation than those living near nuclear power plants because the latter are so well controlled.

- <u>Water pollution</u>. Burning coal contributes to water pollution as air pollutants, including acids, metals and other particulates, are deposited into water.
- <u>Soil pollution</u>. Air pollutants are deposited onto soil too, and may acidify soil. High metal levels can adversely affect soil, including its ability to be farmed.

Follow the life of coal. ■ <u>Mining</u>. Surface mines can ruin local environments. One example is the destruction resulting from mountaintop removal of coal as described in Chapter 1. Underground mining poses dangers to workers, and until modern workplace protections were introduced, coal dust often caused deadly black-lung disease. Both surface and underground mining lead to the exposure of sulfur-containing rocks to the water and air that oxidizes the sulfur to acid. The acid runs off to local water bodies carrying dissolved metals with it. ■ <u>Processing</u>. As coal is crushed, sized, and (sometimes) washed, scarce water may be polluted. Coal mining and processing produce large quantities of waste and air pollutants. ■ <u>Burning</u> was dealt with above. ■ <u>Ash disposal or reuse</u>. About 100 million tons (91 million tonnes) of ash results from burning a billion tons (907 million tonnes) of coal a year in the United States. Much of this ends up disposed of on land or in ponds. With organic matter burnt away, ash has a higher metal content than coal does. Ash leaching can result in acid and metal runoff into the area's water. Europe, and to a lesser extent the United States, uses ash in concrete and building products and in road beds. The environmental impacts of transportation must also be included at each of these stages.

Despite its problems, tremendous reserves of coal exist around the world and its use will continue. The challenge is both to continue to develop clean-coal technologies, *and* to find ways to assure it is used. Even in the wealthy United States many companies resist the use of expensive technologies and in poor countries the problem is much greater.

Petroleum

Petroleum burns more cleanly than coal. However, burning oil produces most of the same air pollutants produced when burning coal. The carbon content of oil, and thus the amount of CO_2 emitted, is less than coal, but more than natural gas. As with coal, we must follow petroleum's whole life. What are its impacts during recovery, processing, using, and disposing or reuse? Remember transportation too, which is of particular importance for petroleum. ■ Transportation. Marine oil spills occur, sometimes with devastating effects. Box 9.3 described the *Exxon Valdez* spill. In late 2002, a monumental spill occurred off the coast of Spain. Ship crew members were reportedly poorly trained, and the ship and its technology were old. Spain suffered its worst ecological disaster ever and said it is essential to develop better safety measures. The Director of the UN Environmental Program, Klaus Toepfer, agreed. Toepfer also noted that the price of gasoline "is not reflecting the true environmental costs of oil." Many countries, the United States in particular, increasingly depend on transport from foreign sources. Land transport is not risk free either. Spills sometime lead to fires or explosions, loss of life, and pollution. As with coal, oil-recovery operations sometimes greatly harm the local environment.[5] ■ Ash. Unlike coal, little ash is produced by burning oil.

Oil will not run out in the foreseeable future, but will become more costly as easy-to-tap sources become depleted. Plentiful now, petroleum is a non-renewable fuel.

Natural gas

Natural gas, compared with coal and oil, has fewer contaminants and burns more cleanly. It also generates only about half as much CO_2 per unit of energy as coal, and one-third less CO_2 than oil. However, burning natural gas does produce NO_x because, recall, NO_x forms during burning and not from internal contaminants; low-NO_x burners are necessary to control it. The primary component of natural gas is the

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[5] Effects on local people, often indigenous groups, can be serious. Oil companies make deals with a central government that does little to benefit local communities although severe environmental degradation may occur and interfere with their ability to fish or otherwise earn a living. In 2002, about 600 unarmed women, many elderly, took over a ChevronTexaco oil terminal in Nigeria occupying its control room, docks and landing area. They threatened to strip naked to shame the oil officials if their demands for help were not met. Many local people subsist in absolute poverty, a dollar a day or less. Because they are uneducated, the oil operation does not hire them, but there are almost no schools to provide education. The facility exports half a million barrels of oil a day, but payment goes only to the Nigerian government and, "much of that money ends up in the overseas bank accounts of the ruling elite; the rest is used to finance an army that both protects the oil facilities and keeps the government in power. Almost none of the revenue ever finds its way to the local populations." ChevronTexaco finally agreed to help provide electricity to the area, build schools, and provide other help.

potent greenhouse gas methane. This is a concern when gas leaks. ■ Natural gas is the fastest growing means of producing electricity worldwide. Its use is expected to double between 1997 and 2020 – although in the United States coal still produces about four times as much electricity. Natural gas too is non-renewable. ■ There is more than one method of recovering natural gas. It is often found with oil deposits and is recovered as part of those operations although it is still sometimes flared off and wasted. A newer method, often harmful to local environments, recovers natural gas from coal-bed deposits. ■ Periodically, natural gas leaks happen during its recovery, transportation, and use. These can result in destructive explosions. Another safety concern is the hundreds of carbon monoxide deaths occurring each year in private homes due to malfunctioning natural-gas furnaces. These occur when burning oil too, but happen more frequently with natural gas.

Reducing pollution by reducing fossil-fuel use

Conservation

Conservation is pollution prevention (P^2). It conserves valuable resources and lowers pollution. There are many opportunities to conserve energy, while also saving money. Some measures are simple, such as turning off unused lights. Sometimes, they are obvious: one facility had only one switch to control lights in two offices; providing a separate switch to each office saved $300 a year. In his book, *Cool Companies*,[6] author Joseph Romm notes that companies – even after having already gone through a careful examination of energy-saving opportunities – can repeat the process and continue to find ways to conserve energy. Increasing *efficiency*, i.e., making a given amount of energy do more, is conservation too. If an individual turns off unneeded lights, this is simple conservation. If an individual leaves the lights on, but buys more-energy-efficient light bulbs this is efficiency. Ideally, people will both turn off unneeded lights and buy energy-efficient ones. Simple conservation saves money immediately. For efficiency gains, one ordinarily must invest money; monetary savings occur over time. If the time needed to recover the investment is a few months or a year, people are more likely to make the investment than if it takes years or many years to recover an investment. This is why many individuals – and businesses, universities, and other institutions too – often don't build optimally energy-efficient buildings. They only consider the up-front costs.

Industrial energy use

■ *Industrial motors* are a major user of electric energy. They are often inefficient and bigger than necessary to do the jobs required of them. In the United States, motors consume 64% of the electricity used by industry. The US Department of Energy (DOE) is working with

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[6] Romm, J. J. *Cool Companies: How the Best Businesses Boost Profits and Productivity by Cutting Greenhouse Gas Emissions*. Washington, DC: Island Press, 1999.

companies to increase the use of energy-efficient motors. In one case, the DOE audited a dozen industrial sites and found that, by installing motors appropriate to the job, average energy use could be cut by one-third with a payback time of 18 months. ■ *Generating steam* is another big industrial user of energy. After generation, the energy in the steam is often not fully used. But recall the example of Kalundborg (Figure 2.2) where the power plant passed unused steam on to other facilities and households who could use it. An increasing number of industrial generators are making more efficient use of the energy they generate. In Jay, Maine the company Androscoggin Energy operates a natural-gas power plant. It is co-located with a pulp and paper mill owned by International Paper. The power plant generates and sells electricity, and it also sells steam to the mill. Both the mill and the power plant use energy more efficiently and save money too. This is an example of *cogeneration*; that is, Androscoggin Energy is generating two forms of useable energy (both electricity and steam or heat) from one source, natural gas. Cogeneration allows a given amount of energy to do more work, and less pollution is produced.[7]

Burning fuel that is naturally cleaner

■ Among the fossil fuels, natural gas burns most cleanly, petroleum is intermediate, and coal burns the least cleanly. Thus, preferentially burning natural gas generates less pollution. However, the most-advanced coal-burning plants reportedly burn almost as cleanly. Carbon dioxide emissions are also lower as natural gas contains less carbon. ■ Some high-sulfur coals produce large amounts of sulfur dioxide when burned. Other coals such as those in some western US states have sulfur contents as low as 0.3%. Preferentially burning the latter coal generates lower sulfur dioxide emissions.

Adopting clean-coal technology

■ Control. A common control technology is using scrubbers to capture sulfur dioxide and particulates (including metals and soot). Recall that 100% of a pollutant cannot be captured, but advanced technologies can capture almost all. Low-NO_x burners cut nitrogen oxide emissions by as much as two-thirds, and newer technology cuts NO_x much further still. ■ Pollution prevention. Using technologies that produce cleaner-burning coal is P^2 as is using technologies that lead to burning coal in ways that allow it to burn more cleanly. Washing crushed coal with water removes some sulfur providing a coal with lower sulfur dioxide emissions. Another P^2 approach is burning coal on a *fluidized bed*. Coal is pulverized and burned along with ground limestone on

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[7] Compare this example of cogeneration to a natural-gas power plant located only a few miles from where this text is being written. This facility vents lower-energy steam (which cannot drive a turbine) into the atmosphere. Especially on cold days, big clouds of steam hang over the area, wasted energy. Another environmental plus at Jay is that the pulp and paper mill was able to shut down its boilers, which had burned Number Six oil, the dirtiest type of fuel, oil and rely on Androscoggin Energy which uses cleaner-burning natural gas.

a screen. Air currents keep coal particles in constant motion, giving the appearance of a boiling or fluidized bed. The ground limestone captures sulfur dioxide as it is generated. A fluidized bed also allows more-efficient burning with fewer byproducts of incomplete combustion.

Modern clean-coal technology can clean coal, burn it efficiently, capture sulfur dioxide, metals and other particulates, and greatly lower NO_x emissions. ■ Compare three pictures. (1) If all coal-burning plants in the United States had no controls, they would emit 20 million tons (18.1 million tonnes) of sulfur dioxide. (2) With the controls they actually use now, they emit about 12 million tonns (10.9 million tonnes). (3) If all plants used state-of-the-art technology, they would emit only 2 million tons (1.8 million tonnes). Companies typically resist spending the money necessary for major retrofits, or to build expensive new plants. This means many dirty facilities remain in operation even in a country such as the United States, which can afford the technology. A number of dirty power plants were "grandfathered" under the first Clean Air Act of 1970; that is, they did not have to install modern controls. But in 2002, they are still operating and producing a disproportionate amount of pollution. At the other end of the spectrum, the new Bruce Mansfield Power Plant in Pennsylvania spent almost one-third of its construction budget on environmental technologies, building a state-of-the-art plant that burns coal much more cleanly. ■ In poor countries the situation can be much worse. In China and India, sulfur is often not removed and air-emission controls are poor. In addition, the pollutants travel; sulfur dioxide emitted in China can have an impact in Japan even though Japan itself uses modern controls.[8]

Except in special circumstances, the greenhouse gas carbon dioxide is not captured from flue gas.[9] And because carbon is an integral part of the chemicals in coal it cannot be washed out like inorganic sulfur. Coal burning produces more CO_2 than other fossil fuels. However, although it of course costs, CO_2 can be captured. Both in the United States and internationally, sequestration is being explored as a means to manage captured CO_2. The CO_2 would be sequestered deep underground in aquifers, in coal seams, or deep under the ocean. A major fear expressed is that the CO_2 so stored will escape back into the atmosphere, and that if sequestered in the ocean it will damage

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[8] A technology being tested in demonstration projects is coal gasification. Here, part of the coal is converted to *syngas*, which is burned to produce electricity. Gasification is not incineration, the whole process is changed. Almost all the sulfur in syngas can be recovered as elemental sulfur, a salable commodity. Mercury can be contained within the system. CO can be converted to CO_2 before it reaches the flue gas, and could be captured if dependable, reasonably priced sequestration techniques were available or if uses were found for the CO_2. Atmospheric emissions of pollutants other than CO_2 would be low. Gasification technology is also more energy efficient than a traditional coal-burning plant; it may be commercialized within the next decade. However, it is more expensive than building a traditional electric power plant.

[9] Sometimes, small amounts are captured for such uses as carbonating beverages or making the calcium carbonate used in paper making.

marine life. Sequestration is also currently very expensive. If sequestration is to have a future, dependable data from long-term projects will be necessary. Other research has a goal that generates less controversy – it aims to incorporate captured CO_2 into useful chemicals. Meanwhile, we must depend on conservation and efficiency to reduce CO_2, and on greater use of the renewable energy sources described below. The greenhouse gas problems of coal are aggravated by coal mining. Mining releases methane, a greenhouse gas 20 times more potent than CO_2.

Conservation and efficiency

Kurt Yeager of the US Electric Power Research Institute, speaking at a gathering sponsored by the Sierra Club[10] (an environmental organization) noted, "We . . . could put an energy infrastructure in place over the next decade that could increase the productivity and efficiency of the US energy system by at least 30 per cent, with a similar level of pollution reduction. This would be achieved not through stringing more wires around the country but by applying the technology we have available to us today to the existing infrastructure." At the same meeting John Browne, Chief Executive Officer of BP Amoco, noted that BP had by 2002 voluntarily cut its greenhouse gas emissions to 10% below 1990 levels, doing so at no net cost to the company. It achieved these results by reducing energy use and improving energy-use efficiency. Browne said that BP's achievement, "is the product not of a single magic bullet, but of hundreds of different initiatives carried through by tens of thousands of people across BP." Notice his point that conservation and efficiency measures were accomplished not by one big step, but by multiple small ones. ■ As important as conservation is, conservation does not end the task. We need to continue to develop more renewable energy. Or, as Kurt Yeager says, "If we like Gulf wars, we don't need to do anything." But, he further said, a sane and sustainable energy policy requires that we must "kick the oil habit."

More energy-conscious individuals

There are so many ways that individuals can conserve or reduce their use of electricity without affecting their lifestyle. A few of these follow. ■ Install compact fluorescent (energy efficient) light bulbs in your home. They initially cost more but, in addition to saving energy they have a much longer lifetime than a typical bulb. ■ Turn lights off when you leave a room. ■ Turn down the thermostat at night. ■ Because clothing dryers are especially high energy users, use natural gas as a more energy-efficient way of drying clothes. And a washing machine that spins more water from clothing means less energy is needed to dry them. Do not wash and dry clothing more than is necessary. ■ Insulate and weatherproof your home, while taking

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[10] Sierra Club. 2002. Beyond Fossil Fuels. http://www.sierraclub.org/200207/forum.asp (accessed January, 2004).

care (Chapter 17) to maintain good ventilation. ■ If Americans used energy as efficiently as the Germans, they could cut energy use in half.

Questions 13.2

1. One American uses as much energy as two Germans, three Japanese, or a dozen or more Indians or Africans. Aside from environmental impacts, are there ethical factors we should consider too? Explain.
2. Cutting greenhouse gas emissions also cuts emissions of sulfur dioxide, nitrogen oxides, and particulates. (a) How? (b) Why is there not an exact one-to-one correspondence between cutting CO_2 emissions and cutting emissions of these other pollutants?
3. What are three energy-conservation steps a business or institution could carry out without cost?
4. What are three ways to use energy more efficiently that do have an up-front cost, but that will pay for themselves over time?

Electricity from nuclear fission

Nuclear power plants produce about 20% of US electric power, and more in France and Japan. In the 29 OECD nations overall, nuclear power produces about 11%. No new nuclear power plants are being built or planned in the United States. In the 29 OECD countries nuclear-power generation is expected to decline somewhat in the coming decades. However, Asian countries, especially, continue to build them.

Nuclear power plants produce no air pollution. Some nuclear-waste components are very long-lived or highly radioactive, but waste volume is very small and solid. Think about objections to nuclear power as well as counterarguments: ■ Nuclear reactors cannot be operated safely. Proponents of nuclear power argue that modern nuclear reactors are different from, and much safer than, those involved in the 1986 Chernobyl accident in the Ukraine. Plants with advanced-reactor designs that take imperfect human operators into account can operate safely. ■ Radioactive wastes cannot be safely disposed. Burial is so controversial that although now, after many years, a burial site in the United States has been selected, it may be many more years before it is used. Proponents argue that nuclear waste can be safely stored, that this concern is political not scientific. It can be vitrified and stored in a deep underground repository in a stable geological formation. (Whether the glass will corrode over many thousands of years while the longest-lived radioactive components decay is unknown.) Proponents point to the Oklo "natural reactor" in the Republic of Gabon. Starting about 2 billion years ago and continuing over a 500 000-year period, natural uranium-fission reactions occurred that created hundreds of tons of nuclear fission products. In 2 billion years, no radioactive materials migrated from the rocks. Critics say there is no assurance that other storage sites would be equally safe.

■ Some nations adopt nuclear power to get access to material for nuclear weapons. This is indeed a problem with some reactors, but not with light-water or boiling-water reactors. ■ Since the 9/11 attacks on the United States, many fear attacks from the air on nuclear installations, which could result in widely broadcast radioactive chemicals. Not everyone believes that such attacks could be successful.

Nuclear proponents compare a 1000-megawatt nuclear power plant with a 1000-megawatt coal-burning power plant. ■ Coal. The coal-burning plant can emit as much as 35 000 tons (31 750 tonnes) a year of sulfur dioxide (although good environmental controls can greatly minimize this). Metals are present in coal only in parts per million. But burning huge amounts of coal – about a billion tons (907 million tonnes) a year in the United States and about 1.3 billion (1.18 billion) in China – means that emissions can be significant in plants with poor environmental controls. Some metal contaminants, such as uranium and thorium, are radioisotopes, and are emitted at levels greater than those permitted for a nuclear reactor. Environmental controls alone cannot reduce the 4.5 million tons (4.1 million tonnes) of carbon dioxide that a coal-burning plant may emit (although coal-burning power plants operating at their most efficient can reduce the amount of carbon dioxide emissions). The coal-burning plant produces 3.5 million cubic feet (2.67 million m^3) of ash a year. Mining coal often entails great environmental damage. ■ Nuclear. The nuclear plant produces only 70 cubic feet (53.4 m^3) of high-level radioactive waste. There is no carbon dioxide or other emissions during operations, except for hot water. However, when the nuclear plant and its components are being built and later when it is dismantled there is some pollution.

Nuclear power might have been less controversial if safety and radioactive waste concerns had been handled early in the history of its use. However, nuclear technology's initial user was the military, who did not consider health, safety, and environmental concerns a priority. Even if we build no new nuclear plants, we must deal with the radioactive waste that is already on hand. In the United States, the great majority of that waste is from old military and US DOE operations. Comparatively, the amount of waste from commercial reactors, and from medical and research operations, is very small. Moreover, civilian power-plant waste is solid whereas much military and DOE waste is liquid, complex, and often mixed with other hazardous waste. These military and DOE sites present tremendously expensive and technologically challenging clean-up problems. Many scientists and engineers urge that we do not give up on nuclear power. They believe that our energy needs and the pollution generated by burning fossil fuels are so great that we cannot dismiss nuclear power. Kurt Yeager of the US Electric Power Research Institute observed, "I believe it would be a tragedy for future generations if we outlaw nuclear power because the current generation of engineering doesn't meet our standards . . . I strongly believe that we need to maintain that . . . option, and . . . move the technology forward, not subsidizing it, but allowing it to move forward on its merits."

Question 13.3

1. Put yourself back in the world of 1945. World War II has just ended after nuclear bombs were dropped on Japan. Your country strongly desires to use nuclear energy for peaceful purposes, and especially to produce nuclear electric power. Consider that you know ahead of time the problems that can arise with using nuclear power: ionizing radiation can harm life, nuclear reactors may not always be safe, and fail-safe operation may not be fail-safe. Even if reactors are safe, human operators are imperfect. Some nuclear-waste components remain radioactive for many thousands of years, and disposing of them raises perplexing problems. Nuclear-power technology can in some cases also be used to develop nuclear weapons. Your nation, nonetheless, believes that nuclear power is desirable. If your country knew in 1945 what we know now, how would it have developed nuclear power in a more environmentally and socially responsible way?

SECTION IV

Electricity from renewable energy

Each renewable energy source has tradeoffs. One renewable source may produce little or no pollution, but have other adverse environmental and social effects. As you read, keep in mind that no one technology can do it all – there is "no magic bullet." A mix of sources will be needed and the task may take many decades. As a Royal Dutch Shell spokesperson remarked, it will be a "messy transition."

Hydroelectric dams

A dam appears to have many advantages. It generates little air pollution and depletes few non-renewable resources. It generates needed electricity, is expected to prevent floods, and is used to provide irrigation water. But a large dam[11] floods agricultural land, drives many people from their homes, deprives downstream wildlife of water or the water temperature which they need, deprives downstream recreational users, interferes with fish migration, and disrupts ecosystems and wildlife habitats both up- and downstream. Although dam builders expect the dams to improve flood control, sometimes changes in water flow lead to less frequent but more catastrophic floods. Using the dam as a source of irrigation water can waterlog the land on which it is used and saturate it with salt. Dams also have safety concerns. Their lifetimes are limited by a build-up of silt. And dams are not pollution free: decomposing organic matter in dam reservoirs generate methane; and reservoir bacteria are unusually active in

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[11] A large dam is one more than 15 m high or one with reservoirs holding more than 3 million m^3 of water. There are over 45 000 large dams in the world. China, which already has a great many of these, is building the biggest dam of all, the Three Gorges Dam on the Yangtze River. It will displace 2 million people.

converting elemental mercury to methylmercury. Dams also often lead to angry confrontations over water use, even if the river flows only within one country. Powerful local people may take all the benefits. Dams on international rivers can cause severe tensions.

In 2000, the World Commission on Dams presented a decision-making framework to guide future dam construction. Their approach is based on more than financial considerations, and analyzes factors such as why a new dam is needed, and whether another option could meet the same goal. It analyzes the various effects the dam will have, makes recommendations to assure that its benefits would be shared and not appropriated by a few individuals, and recommends provisions for people whose livelihoods and homes are destroyed. *Small* dams, depending on the characteristics of each, avoid the worst of these problems.

Questions 13.4

1. Compare the environmental impacts of a coal-burning power plant and a large hydroelectric dam. Why is it difficult to make *direct* comparisons between the two?
2. These difficulties in making comparisons also apply to comparing other sources of energy. How then can society make decisions on how best to produce energy?

Solar energy

Each year, the Earth's surface receives sunlight with an energy content equivalent to ten times more than that stored in all known reserves of coal, oil, natural gas, and uranium combined. We use solar energy when we burn wood and other biomass fuels. We also use solar energy when we burn fossil fuels. Energy represented by the flow of water over dams also originates from the sun's energy (which evaporates the water that subsequently falls onto the earth). The energy of the wind that drives wind machines also comes from the sun.

Solar power

The term "solar energy" as applied to electric power generation refers to either photovoltaic cells or thermal–solar systems. *Photovoltaic* (PV) cells directly generate electricity from light. A *thermal–solar* system generates electricity *in*directly: sunlight is reflected from panels onto collectors. These heat water (or sometimes other substances) to produce the steam that powers the turbines that make electricity. Solar power does not directly pollute, but remember to examine its whole life cycle. Pollution is generated when solar panels are manufactured, transported, and maintained. Other issues include: ■ Workers need protection from the toxic chemicals used to manufacture PV cells. ■ Solar energy is not generated at night and less is made on days with little sunlight so we must store the solar energy. ■ To produce large amounts of electric energy, large land areas would be covered with solar panels. Still, the US Electric Power Research Institute estimates that one-quarter of America's electricity needs could be met by about 6000 square miles (15 540 km^2) of solar farms, an area equivalent to the state of Connecticut. ■ Solar power plants are located in areas where sunlight is plentiful, but must be stored and transported to less-sun-rich locales. This means new power lines, which often lead to confrontations with people not wanting lines near their lands, homes, or schools.

Small-scale operations

Generating solar energy on a small scale can avoid many of the problems associated with large systems. You are probably familiar already with *very* small-scale applications such as powering a calculator, or recharging batteries with a solar-powered charger. Solar power can also partially, sometimes totally, fill the needs of individual homes or buildings although typically some solar energy must be stored in batteries. Although it is costly, households in remote locations or wanting to live "off-the-grid," can generate electricity using small PV set-ups especially in sunny locations. But they must store part of that energy if they want to live off-the-grid, and also typically must use propane to power a refrigerator. ■ The sunny city of Los Angeles, California provides financial assistance to households installing PV grids. A 2-kw PV system generates 60% to 80% of the electricity needs of an average home. Homes remain connected to the conventional power grid too. The utility charges the householder for the electricity that the solar system was unable to generate, and it buys any excess generated. A meter keeps an ongoing account of such transactions. The city's goal is to have 100 000 homes with solar installations by 2010. ■ The Japanese have developed a "solar roof" in which PV cells are an integral part of roofing shingles, and replace ordinary shingles on part of the roof. The solar shingles convert solar energy into direct current (DC) electric energy. For use in the United States, the DC current must be transformed into alternating current (AC) because US homes only use AC. Depending on the amount of sunlight available, a solar roof can provide 60% to 90% of the electricity needs of an average three-bedroom home. The household is connected to the electric grid to meet the rest of its electricity needs. In the United States, some federal buildings are retrofitted with solar shingles. One major example of these still-expensive shingles is the Pentagon roof. ■ Even some residents of the far-northern US state of Maine install PV systems for a portion of their electric power. They store electricity using expensive battery systems.

Hot water

Another practical way to use the sun's energy is to heat water. Water is pumped through roof panels exposed to the sun. Solar energy heats the water, which is then used for household purposes. The amount of hot water produced depends on the amount and intensity of sunshine. In Bogota, Columbia the hot water in many apartment buildings is generated this way. Even in cloudy or northern locales, there is often enough sunlight to heat part of a household's water. ■ Passive solar energy. Even in cloudy or northern locations homes can be built to capture enough solar energy to help meet heating needs. In sunny locales, passive solar energy may overheat places such as sunrooms, and excess heat must be directed away to other parts of the home.

Wind power

Wind machines don't directly pollute, but do generate pollution during their manufacture, transportation, and when access roads are built for them. Unless locations are planned to avoid bird migration routes, turbines can result in bird deaths. Noise is sometimes a problem too. Large tracts of land are needed, but, except for surfaces covered by machines and access roads, the land can be used for crops or trees. They need locales with dependable and strong winds. People may not want to live close to wind turbines, so European nations have begun building offshore turbines anchored to the sea floor. Offshore winds are also stronger. Wherever the turbine is located, winds are not constant and the wind-power electricity may need to be stored. ■ The cost of wind energy has fallen greatly over the years. It could be cost competitive with fossil fuels were it not for other problems. A major problem is transporting the power to customers. Mid-western US states have strong winds, but lack the infrastructure to transport the power that could be produced. ■ The United States generates about 0.5% of its electrical energy from wind although one US state, California, makes at least double that. Some believe it is reasonable to believe that wind could provide 12% of US electricity needs. Wind energy now provides 10% of Denmark's electricity needs, 14% in one German state, and 22% in one Spanish province. However, these locales have strong ties to the larger grid in order to avoid the vagaries of the wind. ■ Although it is not currently a practical alternative, wind power is also touted as a renewable means of making hydrogen fuel.

Small-scale operations

Wind power too can be used in small systems. Recall that windmills were used for centuries in the Netherlands. They were also common on farms in mid-western US states. In both cases they were used to pump water. Modern wind machines are sometimes used to generate electricity for private homes. Some believe that wind machines have a future not clustered on large wind farms, but dispersed among many small farms as an extra cash "crop." They believe too that small wind turbines would fit into urban landscapes.

Question 13.5

1. The cost of wind power is down to 4 to 6 cents/ kW h (in locales where the infrastructure is available) and, worldwide, wind power use has grown 25% per year in the past decade. Nonetheless, it will probably take many years to make great inroads into fossil-fuel use. What could be the reasons for this?

Biomass

Biomass is any organic fuel such as wood, crop wastes or other vegetation, and animal dung, or fuel such as charcoal derived from organic material. Billions of people burn biomass in developing nations, as it has been burned for thousands of years. Countries that are now industrialized once depended on biomass. However, biomass can also be used directly to produce electricity, or indirectly to produce biodiesel, ethanol, or methane (Box 13.4). *If* grown in a sustainable manner, biomass has no net carbon dioxide emissions. This is true because the carbon dioxide released when it is burned equals the carbon dioxide absorbed as new biomass grows. Sustainable growth is difficult to define – we must examine all stages of the life of biomass. Growing a crop often leads to fertilizer, pesticide, and eroded topsoil runoff; irrigation is often needed; and there is concern too that the land may be more valuable if used for agriculture or left to wildlife.

To grow biomass sustainably, there must be careful selection of the crop grown, and of the land used (preferably marginal land not suitable for agriculture). Growing and processing conditions are also very important. Some urge that we grow perennial crops as biomass. Perennials have the advantage that the soil is not exposed to erosion, and little pesticide and fertilizer is needed. To allow the land to remain as a habitat for at least some wildlife, the biomass should not be a row crop such as corn. Biomass fuel is available only seasonally although it may be stored. Without careful control, biomass burning can produce air pollution. ■ In 2001, biomass produced 1.8% of US electricity, and has the potential to produce 5%. Others more ambitiously estimate that biomass could provide 8% to 16% of US electricity without displacing critical food crops. Over many years the economies that are now industrial evolved from using biomass to using fossil fuels. Some now visualize a return to biomass, but a return based upon sound environmental principles.

Box 13.4 | Biomass energy

Using biomass for energy can be done in several ways. ■ Use biomass directly as a fuel. 1. Burn biomass to power electricity-producing turbines: biomass crops used include switchgrass, or agricultural waste such as stover (dried stalks and leaves of a crop). 2. Burn biomass to power motor vehicles: used vegetable cooking oil from restaurants is collected, processed and burned as biodiesel. ■ Ferment biomass to obtain fuel. 3. Treat biomass to release glucose; then, ferment the glucose to *ethanol* and burn the ethanol as fuel. Cornstarch can be the glucose source (cornstarch from corn). Glucose, by a more difficult process, can be obtained directly from the cellulose in crops such as switchgrass. 4. Ferment certain types of waste biomass directly, e.g., when manure is fermented to yield *methane*. Burn methane for cooking or heating or, if large amounts are produced, burn it to generate electricity.

Biomass fermentation leaves large quantities of organic waste, which can be composted. Burning biomass leaves ash, which can be returned to the soil where its minerals are nutrients for new vegetation. These are viable uses, but would need careful monitoring to prevent adverse impacts.

Switchgrass to generate electricity or heat

Almost any carbon-containing material can be burned. Many see switchgrass as an ideal biomass crop in the United States. It is a grass native to mid-western states, needs little fertilizer, and has deep roots that hold moisture and prevent soil erosion. It can grow for 10 or more years before replanting, so the soil need not be tilled (greatly reducing soil erosion and runoff). Burning 1 acre (0.40 ha) of switchgrass to produce electricity can produce annually the equivalent of 2 to 6 tons (1.8 to 5.4 tonnes) of coal. ■ Unfortunately, switchgrass is more expensive than coal. However, switchgrass can also be processed into pellets and burned in specially designed space-heating stoves with 85% efficiency (compared with about 32% when it is burned to produce electricity); this costs less than heating oil. ■ Other potential biomass crops to produce electricity are trees such as poplars, willows, and maples. Grasses and trees provide much better wildlife habitat than does the row crop, corn. Biomass crops are also proposed as sources of motor-vehicle fuel.

Biomass as motor-vehicle fuel

In the United States there is a push to grow more corn in the mid-western states to use as a source of ethanol in gasoline. However, many analysts say that growing, harvesting, and fermenting corn to produce ethanol requires more fossil-fuel energy than the fuel value of the ethanol. And, growing corn, an open-row crop has undesirable effects including soil erosion and fertilizer and pesticide runoff. ■ Professor L. Lave of Carnegie-Mellon University proposes that we instead produce ethanol from switchgrass or agricultural wastes (although the agricultural waste could include corn stover). This is more difficult than recovering fermentable sugar from corn because the sugar is present in cellulose, which is harder to break down into fermentable glucose than is cornstarch. However, agriculturally undesirable land can be used to produce the biomass grasses and trees, and agricultural waste can be used, and the major environmental impacts of growing corn are avoided. Lave proposes that we produce enough ethanol to use as automotive fuel, not just enough to use as an oxygenated gasoline additive. Producing ethanol from these biomass stocks is still in the testing phase.[12]

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[12] Professor Lave envisions that the use of switchgrass and other mid-western native species could do more than just produce ethanol. "A well-planned and thoughtful bioethanol program could return . . . land closer to its native state, enhancing the environment . . . Properly managed, the energy crops could help endangered species and enhance recreational opportunities. This proposal amounts to restoring much of the Great Plains to tall grasses." However, unlike native grasses, these grasses would be mowed annually and used to produce ethanol. Nonetheless, this would leave vegetation for bison, deer, and elk, and the "grasslands and forests would create habitats for birds and other creatures, as well as land for hiking and other recreation." Lave, L. B., Griffen, W. M., and MacLean, H. The (cellulosic) ethanol answer to carbon emissions. *Issues in Science and Technology*, **XVIII**(2), Winter, 2001–2002, 73–78.

Using manure for energy

In countries as different as the United States and Nepal, manure is sometimes fermented to generate methane. Methane can be burned as a cooking fuel; or, when larger quantities are generated, it can be burned to generate electric power. In the United States, New York State is subsidizing farmers to purchase digesters to ferment manure, and use the methane generated to produce electricity for their farms. In the poor country of Nepal, harvesting wood as cooking fuel aggravates deforestation. Fermenting manure and human waste is a partial solution to this problem: it provides methane as a cooking fuel, and the methane burns more cleanly; residues remaining from fermentation can be composted.

Municipal solid waste

One component of muncipal solid waste (MSW) is biomass, and burning it can generate electricity. MSW is available year around, but compared with electricity needs, amounts are small. However, biomass by itself burns more cleanly than as part of MSW. The ash produced by biomass is also less likely to have harmful contaminants than ash from MSW.

Other biomass advantages

If it is grown sustainably biomass can have other advantages in addition to becoming fuel. It could provide new markets for crops while also allowing farmers to manage their lands in more environmentally sound ways than planting only row crops. Biomass could create new technologies and contribute jobs in local economies; it could also provide fuel for electricity in local economies. And if biomass is used to produce ethanol for automotive fuel, it may lessen the dependence on foreign petroleum imports.

Questions 13.6

1. (a) What is an example of how biomass can be used to produce electricity? (b) What is an example of a biomass fuel that can be directly burned?
2. Some visualize burning biomass as a renewable fuel to produce the fuel hydrogen. For this to be a sustainable process, how would it have to work?

Geothermal energy

"Geothermal" refers to the heat below the Earth's surface. The deeper into the Earth's interior one goes, the higher is the temperature. In volcano-rich Iceland or some parts of California, hot water and steam are available close to the Earth's surface and can be used to generate electric power. Such geothermal energy is free of the pollutants that combustion produces, but can release noxious chemicals along with the steam. Local geothermal supplies can sometimes be overdrawn as well. ■ The lower temperatures found in most locales do not yield steam, but can still be used for space heating. If you dig a well, you will find that the temperature within it can be higher than the above-ground temperature, especially in cold climates. Water circulated through the well can be warmed. The water is pumped from the well into a home or other building to warm its interior. If the water's temperature is lower than the desired temperature, additional energy may be added using a heat pump. (The heat pump works in the same way as in a refrigerator, except it works in reverse because you are warming not cooling; electricity operates the heat pump so some outside source of energy, usually from fossil fuels is needed.)

Hydrogen

Fuel cells were discussed above for use in cars. However, they can be scaled to many other sizes to provide electricity for a house or building, even an electric power plant. Using hydrogen to provide electricity for stationary uses is easier than using it for transportation. Nonetheless, major issues remain. One is: Can we use renewable fuels to make hydrogen? Another issue is that a platinum catalyst is now used to make hydrogen. This metal is extremely expensive, and not available in large quantities, so more feasible catalysts are needed. ■ Shell Hydrogen and other companies have formed a California Fuel Cell Partnership to work on hydrogen generation and fuel cells. Government is involved too. In 1996 the US Congress passed the Hydrogen Future Act to fund research and development aimed at making hydrogen fuel cells a practical reality. Other governments too are funding hydrogen-power initiatives.

A hydrogen economy

Iceland heats 90% of its buildings using renewable fuels, i.e., hydroelectric and geothermal energy. Currently, it only uses about 1% of its available geothermal energy. Iceland is now beginning to use geothermal energy to electrolyze water into hydrogen ($H_2O \rightarrow H_2 + O_2$); that is, it will make hydrogen from a renewable energy source. Iceland plans to convert itself into the world's first hydrogen economy. It plans to end fossil-fuel use by 2030 so obviously cars would run on hydrogen too. The city of Reykjavík already has hydrogen-powered buses. Other countries lack Iceland's very practical geothermal supplies. Nonetheless, if Iceland is successful it will have solved other problems too, from which all can learn.

Nuclear fusion

Unlike nuclear fission, nuclear *fu*sion does not use radioactive chemicals. It produces no air pollution. The process produces neutrons, and it is the capture of these neutrons that produces heat. The reaction vessel becomes radioactive during this process, but remains so for a much shorter time than do the isotopes produced by nuclear fission. Research and development for this technology have been extremely expensive and have proceeded very slowly. Congress has funded a joint research program with the European Union, Japan, and Russia intended to demonstrate self-sustaining fusion, and eventually operate a reactor. Some scientists consider the likelihood of successful nuclear fusion to be dim. Others say progress has been steady, and that, "Despite enormous hurdles, the most promising long-term nuclear power source is still fusion." They believe that we may see a fusion reactor within a decade. The US government continues to fund fusion research and development.

Other energy sources

There are many other potential energy sources. The ocean's tidal energy could be harnessed. Some fear that deriving power from tides would disrupt whole ecosystems while proponents believe environmental problems could be overcome. Another means to garner energy from the oceans, perhaps more environmentally sound, is ocean thermal-energy conversion.

Question 13.7

1. Consider the renewable energy sources discussed in this chapter. Pick one that you think should be given priority. Explain your choice, emphasizing why it is among the most environmentally benign.

SECTION V

Fuel for impoverished locales

While energy demand worldwide will increase 60% between 1997 and 2020, forecasts predict a 120% increase in developing countries, especially in Asia, but also in Central and South American countries. China with one-fifth of the world's population only accounted for 8% of world energy consumption in 1999, but this may reach 16% by 2020. If present trends continued, environmental impacts could be ruinous in China and other developing countries. Even now the air of many cities is thick with lung- and eye-stinging pollutants. Fossil-fuel burning occurs mainly in urban areas, but its impact spreads to rural areas and affects crops, trees, and other vegetation. In addition, because pollutants travel, pollutants generated can have an impact in more prosperous regions too.

Although natural gas use is projected to double in the coming two decades, coal is so plentiful that its use continues to increase too. China and India between them have about 2.3 billion people and both have large coal reserves. China's goals include using cleaner coal and more natural gas, generating and using energy with greater efficiency, and installing emission-control technologies. The air in Beijing and Shangai has become somewhat cleaner, but now motor-vehicle use is rising rapidly and cities must grapple with implementing car exhaust standards. Tremendous problems remain in China, but India's may be even worse. Since its 1947 independence from Great Britain, India's economy has increased 9-fold and electricity generation 50-fold. It subsidizes coal production, and coal is used to generate 70% of India's electricity. Few environmental controls are used. Breathing the air in New Delhi is deemed equivalent to smoking two packets of cigarettes a day. India has begun promoting cleaner energy sources such as natural gas, and renewable energy sources including solar and wind energy. It is also building large and very controversial hydroelectric dams (meanwhile China is building the largest and most controversial dam of all). In Mexico, the city of Mexico City with an estimated population of 18 million people, is removing lead from gasoline, and the World Bank is investing $1.1 billion toward cleaner energy and transportation in this city. Brazil too is among the other countries promoting development of less polluting forms of transportation and energy.

Rural areas

Cities in less-developed countries continue to grow tremendously. Nonetheless, nearly 3 billion people still live in impoverished rural areas where most burn wood, crop wastes, and dung. These biomass fuels, says a World Energy Council report[13] barely support basic needs for cooking, warmth, and a little light. Renewable-energy projects offered to these people often fail because technologies are, "too costly, prone to failure, and difficult for local people to repair." The Council urges governments to promote simpler useful technologies such as biomass digesters and gasifiers. The report's authors believe that, although little solar and wind power is used now, these could find good applications. An exception to the use of biomass by the poor is China, where 800 million people burn mostly coal.

Outside assistance

Major changes are needed, but developing countries cannot make the changes alone; in urban areas, especially, some outside assistance is coming in. Shell Oil is an example of a corporation that has started projects in developing countries. Their intent is to gain experience to prepare themselves for future projects under the Clean Development Mechanism (CDM).[14] In one CDM project, Shell is supplying solar roof shingles to 50 000 homes in South Africa. Very recently, the eight wealthiest countries, the "G-8", have shown interest in how developing countries use energy, and are examining barriers to the use of renewable energies in these nations. Many private organizations are also working on simple development projects in impoverished countries. However, efforts are small compared with the need.

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[13] World Energy Council. 2002. Energy Info Centre. http://www.worldenergy.org/wec-geis/edc/open.plx?file= default/default.htm (accessed December, 2002).

[14] The CDM emerged from the Kyoto Protocol. Governments or companies provide money and expertise to help developing countries reduce carbon dioxide emissions. They receive credit for doing so. In reducing carbon dioxide emissions they also reduce emissions of other pollutants.

SECTION VI

Energy present and future

Fossil fuels can produce incredible amounts of pollution, but can be used more cleanly. They can also be used more efficiently. Conservation, especially in developed countries, could be much more widely practiced. Some renewable energy sources including wind, solar, hydrogen, and biomass energy are becoming feasible and their cost more reasonable. Photovoltaic electricity is expensive, now about 20 cents/kW h, but the price may fall to 10 cents within a decade. In the mid-1980s, wind power cost 35 cents/kW h, but is now down to 4 to 6 cents/kW h and is expected to fall further. Biomass gasification (not specifically discussed here) was 7 cents/kW h in 2000, and there are great quantities of potential biomass fuels, including wood waste, agricultural wastes, and manure. Nonetheless, all renewable energies put together account only for 1% to 2% of world electricity. Each has barriers that are slowing its implementation.

Micropower

Micropower means that an operation is providing all its own power, and is entirely disconnected from the central electric grid. Some banks, high-technology firms, or sensitive government operations that cannot tolerate even momentary disruption in electric supply sometimes use micropower. For those that can afford them, fuel cells are sometimes used although the hydrogen is not generated from renewable energy sources. Another way that micropower is provided is by a microturbine fueled by natural gas. The microturbine is less expensive than hydrogen, and some of the steam generated can be used to heat water or for space heating. Other micropower options are being developed, designed for use by small businesses and individual households. The future vision is to develop micropower using biomass, solar or wind energy.

Micropower in impoverished countries

If micropower plants became affordable and practical, they could provide electricity to many of the 2 billion people around the world who now go without. Meanwhile, simple projects can help out in other ways. A small still, for example can purify water in locales that lack electricity, but are rich in sunlight: water is placed in a still; the sun's heat evaporates the water into a collecting receiver, purifying it at the same time. Solar cookers are possible too, but even in sunny climates they may take so long to cook a meal that villagers that have a choice prefer another fuel. Another option may be to generate methane from animal manure.

Government intervention

Eliminating government fossil-fuel subsidies is widely seen as a step that could enhance the use of renewable energy sources. Fossil fuels have long received subsidies in many parts of the world. The European Union is beginning to eliminate subsidies and China has reduced them. In 2008, the United Kingdom will cease subsidizing coal production except for retaining a small industry for national security reasons. ■ Another hindrance to the development of renewable energies is that the environmental damage caused by fossil fuels is not accounted for in their price. Coal especially remains cheap. Governments could help out by taxing activities that degrade the environment. ■ Governments could also provide incentives to conserve energy. Although the EU countries already use less energy than North Americans, they believe they can further reduce energy consumption by 30%. Toward this end, they plan to reduce taxes on energy-efficient products and buildings; implement stricter building codes that promote energy-efficient buildings; promote cogeneration; and promote renewable energy sources. The European Union is also creating a sustainable energy agency. California is among the US states passing legislation to promote renewable energy use. Already 12% of California's electric power comes from renewable sources: wind, solar energy, geothermal steam, small hydroelectric plants, and biomass plants burning wood or other biomass. In 2002, California passed legislation requiring utilities to increase their purchase of renewable power by 1% a year until they reach 20% from renewable sources. ■ Nonetheless, considering the 29 prosperous OECD countries as a whole, it appears that no more than 6% of the energy used by the year 2020 will come from renewable sources such as solar or wind energy.

The future

In the complex and controversial field of energy, we find two points of agreement. (1): Many ways exist to use fossil-fuel energy more efficiently. (2): No one renewable energy source is enough by itself, we need a mix. Some business executives as well as environmentalists have visions of sustainable future energy. John Browne, Chief Executive Officer of BP Amoco speaking at an energy task-force discussion sponsored by the Sierra Club (San Francisco), said: "Any sustainable policy first has to make economic sense. Otherwise, it is very difficult to support. Second, it must speak to the quality of life (especially) with more people on the planet. Third, we need to think about time scales and transitions. How do we get things done in a way that doesn't shock the world financial system, but that achieves an end that is appropriate for the world? Whatever the policy, it must attend to today's problems and recognize that *the easiest, most graphic gain will actually come from efficiencies in the current energy system*. Fourth, it has to recognize that there is a changing mix of energies. Over the history of energy consumption, use has changed and that won't stop. And fifth, the policy should be determined and enabled by a world commitment to innovation and technology." (See http://www.sierraclub.org/powerlunch/.)

David Freeman of the California Power Authority, a discussant at the same meeting said, “We always talk about things that are going to require 25 years and we never begin. Just because it’s going to take a long time to do something is all the more reason to start with some urgency. If, after the oil crisis of 1973, we had decided we wanted to pay attention to nineteenth-century writer Jules Verne, who told us that we were going to eventually get our fuel from water namely, by separating the water into hydrogen and oxygen we would probably have a hydrogen economy by now.”

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Chapter 14

Persistent, bioaccumulative, and toxic

Sustainable development simply means "treating the earth as if we intended to stay."

(Crispin Tickell, British Ambassador to the United Nations)

One chemical category poses special concerns: the *persistent, bioaccumulative, and toxic* (PBT) chemicals. These chemicals also often move among air, water, and land, and cross human boundaries. **Section I** of this chapter examines general characteristics of PBTs. We see that even at low levels, PBTs can present problems. **Section II** examines three families of PBTs that are organic chemicals: polychlorinated, polybrominated, and polyfluorinated PBTs. Metal PBTs are discussed in Chapter 15.

SECTION I

About 87 000 chemicals are in commercial use. The US EPA has identified 53 of these as persistent, bioaccumulative, and toxic (PBT). Of these, 42 are organic chemicals, many polychlorinated. The other eleven are metals.[1] Doubtless others will be identified as additional chemicals are screened. To identify only 53 among 87 000 may seem a small number, but given their potential to cause problems we can be grateful for this relatively small number. Moreover, other chemicals, such as the polychlorinated biphenyls (PCBs), would be classified as PBTs were they still manufactured today. Industrialized countries banned the worst polychlorinated chemicals in the 1970s and 1980s, long enough ago that even though they are persistent, environmental levels have fallen. However, hot spots remain and people are advised not to eat fish caught in the Great Lakes and certain other areas. The Stockholm Convention of 2000 banned or severely restricted 12 polychlorinated chemicals worldwide. ■ Metals. Metals cannot be banned

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[1] For definitions and comparisons of organic and inorganic chemicals see Box 1.3.

in the same way as synthetic organic chemicals because they are not synthesized by humans. Rather they are natural chemicals that have been brought into the surface environment by combustion and mining. However, although metals cannot be banned in the same way as organic PBTs, some are banned from being included in products (Chapter 15).

Red-flag characteristics

Persistence

A persistent chemical – one that does not break down readily – raises a red flag. Even low emissions if they continue, allow a persistent chemical to build up in the environment. As its level increases, the possibility that wildlife or humans exposed to it will take in a larger dose increases too. Most organic PBTs are polyhalogenated; that is, they contain a number of halogen atoms. See Box 14.1.

Box 14.1 | A bit of chemistry

Chlorine belongs to a family of five elements, the *halogens*. These include chlorine, bromine, and fluorine. An organochlorine is an organic chemical that contains chlorine. An organobromine contains bromine, and so on. Many polychlorinated and other polyhalogenated chemicals are PBTs.

Nature produces thousands of chemicals that contain halogens but, with exceptions, nature's chemicals have only one or two halogen atoms[2] or are produced in exceedingly tiny amounts. Conversely, humans have made many polyhalogenated chemicals. Polyhalogenated chemicals *can* degrade, but do so slowly over many years. Thus, if emissions continue they build up in the environment and may bioaccumulate in animal bodies. The polychlorinated insecticide DDT is an example. Its five chlorine atoms are arranged on the molecule in such a way that they hinder the action of enzymes, found in microorganisms, plants, or animals, that might otherwise degrade them. A notorious family of persistent polychlorinated pollutants is the dioxins. The PCB family is another. Chemicals with multiple bromine or fluorine atoms also degrade with difficulty. Depending on the specific pollutant and the conditions in which it finds itself, an organic PBT can take months, years, or decades to degrade. At the poles they may never degrade, but are buried in ice. Box 14.2 indicates some of the multiple problems that a persistent chemical presents.

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[2] One exception is thyroxine, a hormone produced by the thyroid gland. It contains four iodine atoms.

Box 14.2 | Multiple problems

- For a pollutant with a short life span in the environment – i.e., hours, days or weeks – we need only limit or eliminate current emissions. However, such actions are only the first step in dealing with a PBT, we must also deal with that already in the environment from earlier emissions. Illustration: PCBs were banned in the United States in the late 1970s; they still contaminate the environment.
- Many PBTs are emitted *dispersively*. Spraying a pesticide into the air is a dispersive use. The lead that, for many years was added to gasoline is dispersive too because millions of vehicles emit it in their exhausts, and lead particles fall over wide areas. Fossil-fuel combustion can be a major means too of dispersing PBTs hundreds even thousands of miles.
- A hazardous-waste site can be difficult and expensive to clean up, but it has at least the advantage that chemicals are locally concentrated and can usually be cleaned up. Illustration: PCBs that leaked from electrical equipment dumped at a site, or lead that accumulated from an old lead-acid battery recycling site, can be cleaned up.

Bioaccumulation and biomagnification

■ Another red flag is raised if a chemical is *bioaccumulative*; that is, it *bioaccumulates* in living organisms (builds up to levels higher than found in the environment). This happens when a microbe, plant, animal, or human is only very slowly able to break down a chemical or if the chemical finds a site within the body that firmly binds it. Illustration. PCBs are difficult to break down, and being fat soluble accumulate in fatty tissues. The metal lead does not break down at all and the body, treating it like calcium, incorporates it into bones and teeth.

■ Animals excrete water-soluble xenobiotic (foreign) chemicals in their urine. If the xenobiotic is not water soluble, enzymes attempt to convert it into a form that is water soluble, which can be excreted in urine (Chapter 3). Illustration. Polychlorinated chemicals are only slightly soluble in water, but are soluble in animal and human fat, and in the fatty cuticle of plants, and thus tend to accumulate in fat to concentrations greater than found in the environment. A chemical undergoing *biomagnification* reaches progressively higher levels in the fat as it moves through the food web (See Figure 3.3). ■ Some metals bioaccumulate too, but not in fat. *Lead* concentrates in bones and teeth. *Cadmium* builds up in the kidneys. *Mercury* attaches itself to proteins in many locations, especially in the liver.

Toxicity

Researchers agree on definitions for persistence and bioaccumulation, but there is not a common definition for toxicity. The type and degree of toxicity varies with each PBT. One type of toxicity that some PBTs have (including dioxins, DDT, and PCBs) is as environmental hormones (Chapter 3). Other PBTs show different types of toxicity. Indeed, although dioxins, DDT, and PCBs can act as environmental hormones, they demonstrate other behaviors too. Illustration. DDT has low acute toxicity in mammals, but dioxin (2,3,7,8-TCDD) demonstrates extreme acute toxicity.

PBTs often travel

PBTs would present fewer problems if they did not also travel. ■ Organic PBTs. Many polychlorinated organic chemicals show *volatility*. They evaporate from land or water or, in the case of pesticides, may be sprayed into the air. Wind currents then carry them a few miles, or hundreds or thousands of miles from the point of emission. They cross man-made borders as they move. A polychlorinated pesticide sprayed into the air in Latin America may travel thousands of miles north from its point of use via a "grasshopper effect" (Chapter 1), and a portion ends up in Earth's polar region. Polychlorinated chemicals may also move north in migrating fish and animals. ■ The result of these various movements is that PBTs are found concentrated in the fat of Arctic seals and other marine mammals – including Arctic people. This is true though polychlorinated chemicals were not used there. The blood of the Inuit, an indigenous people of northern Quebec, contains levels of polychlorinated chemicals up to 70 times greater than found in individuals living in southern Quebec. ■ Metal PBTs. With the exception of mercury, metals are not volatile in the way that many organic chemicals are. But they travel anyway: emitted as fine particles during combustion, metals move with the wind a few, or hundreds or thousands of miles, and contaminate points far from their origin.

SECTION II

Persistent organic pollutants (POPs)

A POP is a persistent organic pollutant (Box 14.3). Many of the POPs so far identified are polyhalogenated, especially polychlorinated. In the laboratory, a POP is more soluble in *octanol* (an oily substance used as a substitute for fat) than it is in water: the POP bioaccumulates in living fatty tissues. A POP has an environmental half-life greater than one month, sometimes much greater.

Box 14.3 | Two related acronyms

Don't be confused by the two acronyms PBT and POP. The acronym *PBT* stands for persistent, bioaccumulative, and toxic. A PBT substance can be either organic or inorganic (see Box 1.3). Another acronym, *POP*, stands specifically for organic chemicals that are persistent; that is, a POP is an organic PBT.

Reducing the worldwide risk of organic PBTs

In December 2000, after years of negotiation, representatives of 122 countries finalized a treaty, the Stockholm Convention on Persistent

Organic Pollutants (POPS). This banned or greatly limited 12 chemicals, the so-called "dirty dozen." It was agreed that these 12 posed greater risks than some other POPS. Thus, they were the first to be banned although others may be banned in the future. This treaty was the first-ever global agreement to abolish a class of chemicals. ▪ All 12 chemicals are polychlorinated, and 8 are pesticides. ▪ The 8 pesticides are aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, mirex, and toxaphene. ▪ There were 2 industrial chemicals (PCBs and hexachlorobenzene), and 2 byproducts of combustion and industrial processes (dioxins and furans).

Most of the dirty dozen had already been banned in industrialized countries, but were still used in countries such as India and Latin American countries. For the treaty to work, industrialized nations must assist less-developed nations. They thus agreed to provide about $150 million a year and technical assistance to help phase out production and use of the banned chemicals, to destroy existing stockpiles, and, sometimes to help set up production of alternatives. Delegates also continue working on a list of candidates to ban in the future.

Exceptions to the treaty

▪ DDT, one of the dirty dozen, was banned many years ago in Western countries. However, at the urging of malaria experts, the treaty allows poorer countries to continue using DDT to control malaria-bearing mosquitoes. ▪ PCBs were used in electrical equipment for many years, and are still found in old electrical equipment. The treaty allows use of this equipment to continue until 2025, if properly maintained to prevent leaks. ▪ Another of the dirty dozen is dioxins for which the treaty has, "the goal of their continuing minimization and, when feasible, ultimate elimination." Dioxins cannot be banned because, except for laboratories making tiny amounts for research work, no one deliberately makes them. Dioxins are inadvertent byproducts of combustion, of bleaching with chlorine chemicals, and several other industrial processes. Although we cannot ban dioxins, we can modify processes that produce them and thus can often virtually eliminate emissions. Pesticide production processes that once produced dioxin byproducts have been modified or eliminated. In addition, current methods of bleaching wood pulp have eliminated or greatly lowered dioxin formation. As some of these reductions were started decades ago, environmental levels and body burdens of dioxins have decreased.

Reducing risk via the Toxic Release Inventory

Recollect the Toxic Release Inventory (TRI, Chapter 2). Previously, US facilities did not need to report POP emissions as none are made or released in the quantities (many thousands of pounds) characteristic of other TRI chemicals. However, as of 2000, the US EPA requires a facility to report if, in any given year, it makes, uses, or releases 10 lbs (22 kg) or more of any of 27 specified PBTs, including the dirty dozen. ▪ The EPA also developed a *PBT Profiler* to help a company screen chemicals to identify those with PBT properties. ▪ Large chemical companies including DuPont, Proctor & Gamble, and Dow already screen chemicals for PBT properties when they develop new chemical products. This is an example of "green chemistry" – deliberately designing chemicals or processes to use or to produce more environmentally benign chemicals.

Three families of POPs (organic PBTs)

Discussed below are three families of persistent, bioaccumulative, and toxic organic chemicals. The first, PCBs, have been frequently mentioned in this text. The second, polybrominated fire retardants, are still in use. The use of many chemicals in the third family, polyfluorinated perfluorooctane sulfonates, is now being phased out.

The ubiquitous PCBs (polychlorinated biphenyls)

The PCBs are a family of 209 chemicals.[3] Each PCB varies in the number and location of its chlorine atoms. It is the heavily chlorinated PCBs that are most environmentally persistent, and that most-heavily concentrate in animal and human fat. A major use of PCBs (sold as a mixture called Aroclor) was to insulate electrical equipment, as they are non-flammable even at high temperatures. Indeed, safety codes once mandated their use. PCBs were used too in paints, inks, adhesives, newsprint, carbonless duplicating paper, even deep-fat fryers. However, as it became clear that PCBs were persistent and bioaccumulative, and were harming wildlife, the United States banned PCBs in the late 1970s, after 40 years of manufacture. ■ By then several hundred million pounds (of about 1.4 billion lbs manufactured in the United States) had become environmental pollutants. Previously, manufacturers had legally released PCB-containing waste. New York's Hudson River suffered heavy pollution. Contamination was even worse around Anniston, Alabama where PCBs were manufactured for 40 years. Many locales around the Great Lakes and marine coasts were also significantly polluted. ■ PCBs often leaked too from old electrical equipment. The result is that they are major pollutants in 20% of US high-priority hazardous-waste (Superfund) sites. PCB manufacture continued until 2001 in less-developed countries, when the Stockholm Convention was passed.

PCB toxicity

The toxicity of a few PCBs is comparable with the more toxic dioxins. Depending on dose and the particular PCB, they can damage neurological and immunological systems, the liver, and the thyroid gland. Many workers, who were heavily exposed to PCBs over the years they were manufactured, developed liver damage. Many also developed *chloracne*, a form of acne resulting from prolonged contact with organochlorine chemicals, especially PCBs and dioxins. Chloracne can

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[3] Don't confuse the acronym PCBs with PBTs. However, PCBs are one PBT!

be severe and can last for many years. Moreover, the US EPA and the WHO classify PCBs as probable human carcinogens.

PCBs cycle in the environment

PCBs concentrate in sediments from which they slowly move into the water above. From water they escape to air, are windborne elsewhere, are deposited back into water, and then concentrate in sediments again. They can also leave their sediment sink when bottom-feeding organisms take them up, allowing PCBs to begin movement through the food web. They also escape during dredging operations.

Exposure

Environmental levels are much lower than in the 1970s, but PCBs remain ubiquitous contaminants in the United States and worldwide. Exposure to PCBs occurs today mainly via eating fatty meat, milk, milk products, and fish. Since banning production in the United States, PCB levels in Great Lakes fish fell by up to 90%, but many fish still contain levels in excess of 2 ppm (the US FDA standard for PCBs in commercial fish) and are considered unsafe to eat. Nonetheless, people still catch and consume PCB-contaminated fish in the Great Lakes; for them, fish are the major source of PCB exposure. PCBs still rank as high-risk chemicals in the Great Lakes, the Arctic, and several other locales.

A half-a-billion-dollar risk-reduction project

From the 1940s to 1977 two General Electric (GE) plants on New York's Hudson River manufactured PCB-containing electrical equipment. They released over 500 tons (454 tonnes) of PCBs into the Hudson. Fish in the most contaminated section had 2 to 41 ppm PCBs in their flesh, compared with the FDA's standard of 2 ppm. The fish themselves also sometimes showed obvious harm – 90% of one codfish variety developed liver tumors by adulthood. Other fish suffered DNA damage similar to that seen in some human tumors. In 1984, the US EPA declared a 200-mile (322 km) section of the Hudson River a Superfund site. GE officials insist that the river has been cleaning itself and is continuing to do so. In 2000, the EPA did find the river cleaner than in earlier years. However, PCB fish contamination was still above levels considered safe for women of childbearing age and small children. Consideration was given to capping the heavily contaminated sections of the river with clean sediments culled from elsewhere. However, the EPA believed these sections were too turbulent for capping. In 2001, after 10 years of research costing $25 million and exhaustive scientific review, the EPA ordered GE to dredge sediments from a 40-mile long section of the Hudson at an estimated cost of half a billion dollars. GE called the plan "absurd," and claimed that dredging will only stir up sediment PCBs. In its response, the EPA said it would regularly evaluate PCB levels in sediment and river water to decide whether to continue dredging.

Questions 14.1 | Obvious versus subtle toxicity

Taiwan

In 1979 about 2000 people in Taiwan suffered PCB poisoning after ingesting cooking oil accidentally contaminated with PCBs and furans.[4] Children born to poisoned women within 7 years showed abnormal skin pigmentation, impaired mental development, impaired muscle movements, and slower growth. The severity depended on how much oil their mothers were estimated to have eaten. Some children appeared clearly poisoned.

United States

Now think about children in the United States born to mothers who had eaten large amounts of PCB-contaminated fish from the Great Lakes. Their PCB dose was low compared with the Taiwanese children. However, trained observers, examining these infants and small children for possible developmental defects correlated to their exposure detected small differences in memory and learning ability as compared with control children. They also reported that the infants were more distractible, and had poorer muscle tone. Commenting on these studies, one researcher stated that the link between prenatal PCB exposure and developmental neurotoxicity was strong – that low-level environmental exposure of the fetus could indeed affect their health. Others, analyzing the same studies remained unconvinced that the reported effects were even real.

Because the United States has not used PCBs since the late 1970s, and PCBs are now banned worldwide, some believe they are no longer important. For adults, exposure to PCBs at current environmental levels is not considered a threat.

1. On the basis of the limited information here, explain whether you believe that women of childbearing age should be warned not to eat fish caught in the Great Lakes.
2. What if family income is low and the fish are an important dietary source of protein and other nutrients – would this affect your response?
3. PCBs, dioxins, and furans concentrate in fat. How could the fish be prepared or cooked to remove or reduce at least a portion of the fat-soluble chemicals?

Polybrominated chemicals, valuable fire retardants

The poly*brominated* chemicals (polybrominated diphenyl ethers, PBDEs) are widely used. They function to prevent or retard fire in electrical equipment, electronics, automobiles, furniture, plastics, and textiles (Box 14.4).

- Toxicity. When laboratory animals were exposed during gestation to high doses of PBDEs, their offspring showed damage to their thyroid and nervous systems. The doses used were much higher than environmental levels.
- Environmental contamination. This is increasing rapidly. Canadian scientists report that PBDEs are reaching the Arctic more quickly – presumably by the grasshopper effect – than dioxins or PCBs, and

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[4] Furans are in the dioxin family of chemicals.

accumulating in seals and other wildlife. Their levels also continue to rise rapidly in fatty tissues of fish in Lake Ontario and the Baltic Sea, and in marine-mammal fat. Japanese, Israeli, and Spanish investigators report increasing levels in human fat. In 1999, Swedish researchers found PBDEs in women's breast milk at levels 60 times higher than in 1972. In Norway, PBDEs were detected in the blood of small children at levels several times greater than in adults. PBDEs also taint foods such as fish, milk, and eggs. Their levels are increasing, just as PCBs, dioxins, and DDT levels are decreasing.
- How did PBDEs become pollutants? This is uncertain, but they represent 5% to 35% by weight of the products in which they function as fire retardants: upholstery, carpets, and other items. Although not very volatile, they do slowly outgas from these items. In addition, when discarded into landfills, these polybrominated chemicals may leach out and find their way into water bodies.
- PBDEs with five bromine atoms. These are the most common contaminants. Such PBDEs are incorporated into polyurethane foam in products such as seat cushions. As these crumble with age, PBDEs may become pollutants.

PBDE levels are still low. Nonetheless, their ubiquitous presence in the environment, and rapidly rising levels, raises alarm.

Reducing the risk

The European Union may ban some uses of polybrominated fire retardants, but controversy remains as to whether to ban all PBDEs or only those found in the environment at higher concentrations.

- Some European electric and electronic companies have stopped using PBDEs. Other industrial users say no substitutes exist for their particular products.
- The United States does not regulate PBDEs, but is evaluating risks to children.
- In addition to the dozen polychlorinated POPs already banned or severely restricted by the Stockholm Convention, some polybrominated chemicals may also be banned as negotiations continue.

Box 14.4 | A bit of chemistry

Small chemicals are often incorporated into plastics as *plasticizers*. Their function is to soften plastics, make them pliable. Another group of small chemicals (commonly the PBDEs) are incorporated into products as fire retardants. Because plasticizers and fire retardants are not chemically bonded to products, they are not held in place – they can volatilize or leach out. This can lead to both human and wildlife exposure. To avoid this, it is sometimes possible to chemically bond flame retardants or plasticizers to the products. Bound chemicals are less likely to leach out.

A polyfluorinated mystery

In May 2000, the manufacturer 3M Corporation took a surprising action. It withdrew its popular fabric stain repellant, Scotchgard™

from the market. Scotchgard contained *perfluorooctane sulfonates* (PFOS). PFOS are a family of about 300 poly*fluorinated* chemicals (Box 14.5). 3M is also phasing out the use of PFOS for fire-fighting foams, mining and oil-well surfactants, herbicides and pesticides, and to prevent food from sticking on paper surfaces such as pizza boxes and popcorn bags. Withdrawals occurred after researchers found PFOS at trace levels in human blood. This included the blood of 3M's own managers, who had not been directly exposed to PFOS. Trace amounts were also found in human blood and animal tissues around the world. How this widespread exposure to PFOS has happened is still a mystery although explanations have been proposed. For the time being many products still contain perfluorinated chemicals.

Box 14.5 | A bit of chemistry

The 'per' in *per*fluorooctane sulfonates indicates that these chemicals contain as many fluorine atoms as they can accommodate; that is, they are fully fluorinated. The fluorine–carbon bond is extremely stable, one of the strongest chemical bonds known. This accounts for its great usefulness. It also accounts for its great persistence.

One researcher said that fluorine was introduced into chemicals although, "what we know about fluorine chemicals in the environment is less than what we knew about chlorine chemicals in the 1950s." What we do know raises concerns.

- Persistence. PFOS are extremely difficult for living organisms to degrade. One researcher believes they, "will redefine persistence," making PCBs and DDT seem easy to degrade in comparison.
- Bioaccumulation. In a year 2000 accident near Toronto, there was a spill of fire-fighting foam containing perfluorinated chemicals. Researchers took advantage of the spill to study fish in a contaminated stream. They found PFOS in fish livers at concentrations 6300 to 125 000 times greater than its water concentration. So these chemicals are bioaccumulative.
- Toxicity. Rats and rabbits exposed to high doses ate less and had reduced body weight. Their litters were smaller and their fetuses gained less weight. Because PFOS chemicals are chemically inert, this toxicity was unexpected.
- Traveling pollutants. How the non-volatile PFOS ended up in birds in the Pacific Ocean, and in animals in other isolated locations is a mystery.

Reducing the risk

3M Corporation is phasing out production of most PFOS chemicals. It is also developing a non-fluorinated Scotchgard. 3M could not totally eliminate PFOS production because of a critical use in airline brakes, for which no effective substitutes exist. The US EPA believes that quick phase out of PFOS chemicals will lead to a quick decrease in exposure too. The EPA may regulate some PFOS chemicals. It also hopes to require businesses to notify the EPA if PFOS chemicals are manufactured, exported, or imported. The agency is also working with regulators in other countries in assessing PFOS risk. They hope to persuade companies outside the United States not to produce PFOS since US production is now discontinued. Meanwhile, although not believing that current exposures pose an immediate health risk, the EPA would be seriously concerned if PFOS production continued.

Questions 14.2

1. (a) Manufacturers state that PBDEs should not be banned because fire prevention is so important. Explain if you agree that their reasoning is legitimate. (b) If no suitable substitutes are available and we continue to sell PBDEs, are there possible ways to lessen their risk?
2. Consider the Scotchgard story. What, if anything, went wrong here? How can we prevent such happenings in the future?

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Chapter 15

Metals

> "Society is a partnership not only between those who are living, but between those who are living, those who are dead, and those who are to be born."
>
> *Edmund Burke, 1790*

All metals are persistent. However, not all metals are PBTs; that is, not all are also defined as bioaccumulative and toxic. Many factors affect whether exposure to a metal poses problems. A higher dose is, of course, more likely to cause adverse effects than a low dose. Another factor, illustrated by the metal, chromium is the chemistry. Chromium(III) has a valence of three.[1] It is a nutrient and, because it is not very soluble, doesn't build up to high concentrations in water. But chromium(VI) has a valence of six, is toxic and is a carcinogen.

- Five nutrient metals are PBTs: *copper, chromium, nickel, selenium*, and *zinc*.
- Six *non*-nutrient metals are also PBTs: *antimony, arsenic, beryllium, cadmium, lead*, and *mercury*. The toxicity of these metals too varies with chemical form as illustrated by lead. *Elemental lead* is toxic, but *tetraethyl lead* is much more toxic.

Section I of this chapter is a metal primer, providing information on metals regardless of whether they are PBTs. **Section II** details four especially troublesome metal PBTs: lead, mercury, cadmium, and arsenic.

SECTION I

A metal primer

Metals are *elemental* and cannot be destroyed. But they do bond to other elements (thus becoming molecules) and then show properties different from the parent metal. Consider three cases.

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[1] Valence has to do with the number of electrons in the outer shell of an element. The valence is important in determining how the element will react with other atoms.

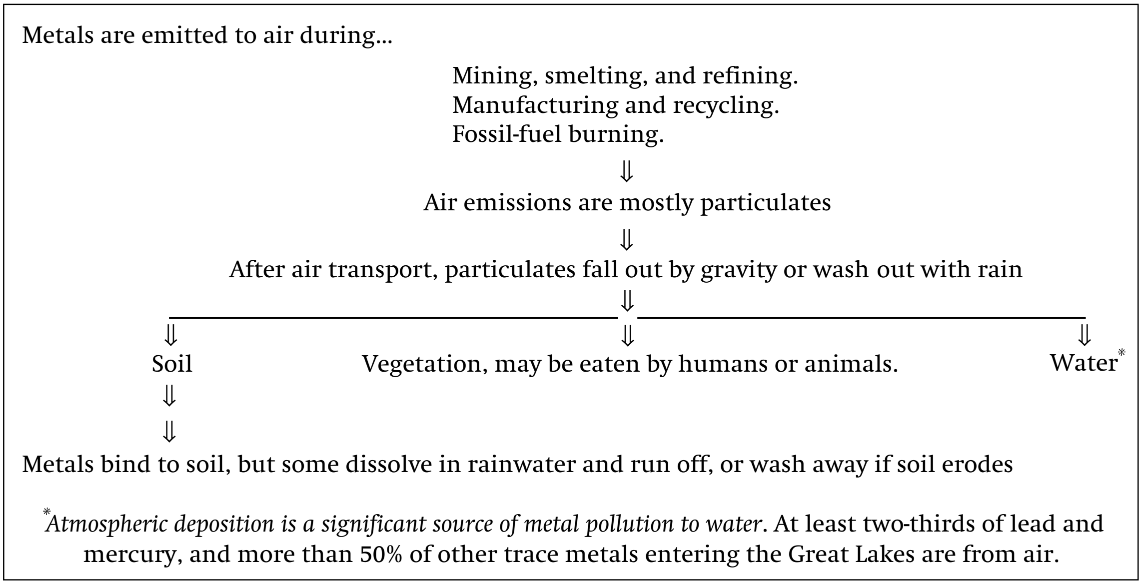
1. *Elemental lead* is a solid, but the molecule *tetraethyl lead*, an antiknock agent, is an oily liquid. The lead is still there, but is bonded to carbon and has different properties.
2. You may be familiar with elemental iron. When iron reacts with other elements, its color and other properties change. A common iron compound is iron oxide (*rust*, a reddish substance) formed when iron reacts with atmospheric oxygen and bonds to oxygen.
3. Think about metal pollutants in soil, at concentrations too great for safe agriculture. In some cases we add lime (calcium oxide) to the soil. The polluting metals react to become metal oxides, which are not easily taken up by plant roots. However, if the treated soil later becomes acidic – perhaps after a prolonged time of acid deposition – the metal may again become soluble.

Metals in soil and sediment

Metals are natural substances found, usually at low levels, in soil. However, metals emitted by mining, combustion, or other industrial processes may reach the soil and increase metal concentrations to unnatural levels. Because metals don't degrade you may expect that once they are in soil, they are there indefinitely. However, changes in concentration can occur in various ways: ■ Contaminating metals in surface soil are buried by the slow build-up of overlying soil. ■ In surface soil, rain may partially leach out soluble metals and carry them away in runoff; or water may erode and carry away the soil with its bound metals. ■ In water-body sediment too, metals over time become progressively more deeply buried as overlying sediment builds up. They may be buried enough to no longer pose a problem – unless the sediment is stirred up, for example when a harbor or river is dredged. ■ Even in sediment, especially near the surface a metal may cause problems. An illustration is mercury. Some bacteria convert elemental mercury to the more toxic methylmercury, which can be taken up into the food web.

Metals in food and water

Metals are naturally found in food and drinking water. Indeed nutrient metals (iron, chromium, copper, cobalt, manganese, molybdenum, nickel, selenium, vanadium, and zinc) are desirable – up to a point. However, at doses higher than those needed for nutrition, metals can be toxic (Figure 3.2) Think of iron, a nutrient. Iron can be a poison and still occasionally kills small children who find and eat their parents' iron-supplement capsules. Natural metal levels can also pose risks when soil or water levels are unusually high. ■ However, human activities are responsible for the dramatic increases in metal levels in the environment seen in the twentieth century. That century saw the mining of about 90% of all cadmium, copper, lead, nickel, and zinc ever mined. The metals lead, cadmium, and mercury pose special concerns, but others that sometimes present problems



Metals are emitted to air during...

Mining, smelting, and refining.
Manufacturing and recycling.
Fossil-fuel burning.

⇓

Air emissions are mostly particulates

⇓

After air transport, particulates fall out by gravity or wash out with rain

⇓

Soil ⇓ Vegetation, may be eaten by humans or animals. ⇓ Water*

⇓

Metals bind to soil, but some dissolve in rainwater and run off, or wash away if soil erodes

Figure 15.1 The fate of metals emitted to air

**Atmospheric deposition is a significant source of metal pollution to water*. At least two-thirds of lead and mercury, and more than 50% of other trace metals entering the Great Lakes are from air.

include antimony, cobalt, copper, manganese, molybdenum, nickel, selenium, vanadium, and zinc.

Box 15.1 | Ambiguous term

The term "heavy metal" is often used to refer to problematic metals such as lead, mercury, cadmium, chromium, etc. However, this term is imprecise.[2] Recently, an alternative term "toxic element" has been used. However, as you saw in Chapter 3 toxicity depends on many factors. So in this text the term "hazardous metal" is used – recall the difference between a hazard and a risk.

Sources of metal pollution

Mining

Mining operations contaminate air, water, and land.

- Air. With the exception of mercury, metals are usually emitted to air as particulates. Notice (Figure 15.1) how significant is the atmospheric deposition to water and land.
- Water. Mining leaves huge quantities of overburden (previously overlying material). Metals leached by rainwater from overburden and other mining wastes can run off to water. Both coal- and metal-mining wastes are often rich in sulfur. If moisture and oxygen are present, sulfur is oxidized to sulfuric acid; then it too can be carried

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[2] If you have lifted a lead brick you can appreciate the term, heavy metal (as compared with a light metal such as aluminum). But several nutrient metals such as iron are "heavy" too; and arsenic, although it has a density high enough to be called "heavy," is a metalloid, i.e., it has both metal and non-metal properties.

away in runoff. Metals and acids can foul streams and rivers for many miles downstream.

- Land. Unless land is properly managed during mining, and carefully reclaimed afterwards, it may become useless for other purposes due to high metal levels.

Remember the whole life cycle. Mining, smelting (melting an ore to separate out the desired metal), and refining (purifying the metal) represent but the first stage of a metal's life cycle. The metal is used to manufacture metal-containing products. Later the products may be recycled, which can result in metal pollution too. Incinerating waste metal products with trash may lead to metal particulates escaping into the air (Figure 15.1). Dumping them may lead to their corrosion and slow dissolution, which also pollute.

Box 15.2 | Ancient mining

Most metal mining occurred in the twentieth century. However, humanity is fortunate that the ancient Greeks and Romans didn't mine and smelt as much ore as their twentieth-century counterparts. The ancient Romans smelted metal ores over open fires with emissions so noxious that authors of the day complained of them. Lead and copper pollution from thousands of years ago is still detectable around the world today, recorded in buried layers of ice, bogs, and sediment. In the sixteenth century, large furnaces with tall stacks were developed. These still badly polluted their surroundings, but were an improvement over ancient methods. Without careful controls, modern mining, smelting, and refining can still pollute badly.

Fossil-fuel combustion

Metals are also emitted during combustion of fossil fuels. However, even coal, the fossil fuel with the highest metal content contains only trace amounts, so emissions at any moment are small. However, large quantities of coal are burned, year-in year-out, so even trace emissions build up, especially near combustion sources. A billion tons (907 million tonnes) of coal is burned each year in the United States alone, and more than that in China. Petroleum has a lower metal content than coal, but also emits metal pollutants when burned.

- Air. Metals are emitted as particulates or are attached to other particles (except for mercury, much of which is released as vapor). Some metals travel long distances: in the 1950s, pilots flying in the Arctic in winter saw a haze so heavy it obscured visibility; later, the haze was found to be composed of particles transported by winter winds from industrialized regions in Europe and Asia. The haze contained not just metals, but also soot, soil particles, and persistent organic pollutants (POPs).
- Water and land. Metal particulates eventually settle onto land or water (Figure 15.1). Fallout from fossil-fuel burning is especially important near the source.

- Land. Coal-burning plants produce immense quantities of ash. Because the organic portion of coal has been burned away, metals in ash are more concentrated. Ash disposal is a problem. Unless protected, metals can leach out and run off with rain into local water. Unprotected ash can blow away.

Other sources

■ Municipal and industrial wastewater-treatment plants are point sources of metal pollutants to water. ■ Paved roads and construction sites are among the sources from which metal particulates can be blown away in the wind or run off with rainwater. ■ Metal-containing wastes disposed of on land are a source of pollution. ■ Some fertilizers, pesticides, sewage sludge, and animal wastes applied to soil have higher metal concentrations than natural soil levels.

Natural sources

These include volcanoes, forest fires, and sea-salt sprays. These are significant, but it is human activities that are increasing the environmental load of metals.

Where can metal pollution present concerns?

- Fresh water. Even quite small levels of metal pollutants can pose problems to freshwater bodies, with their low amounts of metals. Fresh-water organisms evolved with low metal levels, so higher concentrations can cause adverse effects. Moreover, many lakes have small volumes or few outlets to dilute or displace polluting metals.
- Marine waters. Metals in marine waters are naturally higher than in freshwaters. Nonetheless, ever-growing coastal populations have led to increasing marine pollution coming from runoff from developed land, and rivers carrying pollutants.
- Cities. Older cities had more metal-processing facilities than did rural areas. These left some city soils highly polluted.
- Agricultural soils. Some European agricultural soils, even in Western Europe where pollution is better controlled, are above or close to the *maximum loading rate* for some metals. Above that rate, the soil is not fit to grow crops. Some agricultural villages in Eastern Europe are deserted due to metal contamination. In Japan, metal contamination has made nearly 10% of rice-paddy land unusable. The cost to remediate metal-contaminated soil is high. Large areas may be impossible to clean up.
- Hazardous-waste sites. Lead, cadmium, mercury and arsenic are four of the ten most common pollutants found at US hazardous-waste sites.
- Connection to acid rain. Acid can worsen the risks. Bacteria convert more elemental mercury to the highly toxic methylmercury in acidified lakes. Metals – aluminum is a prominent example – become more soluble in acid soils. Subsequently washed out by rain, metals run off into nearby water bodies and may damage aquatic life.

Human exposure

Human exposure to metals occurs in various ways. Fish consumption is the major route of exposure to mercury. Shellfish, if eaten frequently, may be the major route of exposure to cadmium; for smokers, however, tobacco is the major route of cadmium exposure. For most of us, food is the highest source of arsenic exposure, typically arsenic from natural sources. However, recall that many millions around the world are exposed to arsenic-laden well water. For them, drinking water is the most significant source of exposure. Adverse health and environmental effects vary with each metal. Several of these are discussed below.

Treating diseases with metals

As with other chemicals, metal toxicity depends upon the dose absorbed into the body, nutritional status, and many other factors. Long before antibiotics, arsenic was used to treat syphilis. Not surprisingly patients receiving high doses were sometimes poisoned. Metals still have medicinal uses. Bismuth, as in Pepto Bismol treats some stomach problems. Gold is sometimes used to treat rheumatoid arthritis, lithium for manic-depressive illness, and zinc is found in some drugs. ■ More dangerous situations arise when hazardous metals – such as lead, mercury, cadmium, and arsenic – are used in “folk remedies.” Some Caribbean religions such as Santeria see mercury as a marvelous substance attracting good and repelling evil. Thus, they sometimes use it in medicine. Poisoning cases have been reported among US immigrants who imported metal remedies with them. A well-balanced diet can help protect against ingested pollutants including metals (Box 15.3).

Box 15.3 A healthy diet can reduce risk

A diet emphasizing fruits, vegetables, and grains provides many benefits including a lessened susceptibility to infections and toxic substances such as metals. A varied diet contains a variety of metals including, but not limited to, nutrient metals. Some metals oppose the biological effects of others. Dietary calcium and iron inhibit lead absorption from the gut into the bloodstream. Zinc antagonizes some toxic effects of cadmium. Selenium provides some protection against the adverse effects of mercury, cadmium, and silver. Selenium may lower cancer risk too. A diet high in calcium, iron, and fiber is associated with lower blood levels of cadmium. In the arsenic poisonings described in Chapter 10 (Box 10.3), people with good nutrition were less likely to develop skin lesions even when their drinking water contained high arsenic levels.

Such examples demonstrate the need for a varied diet. However, a healthy diet is often not available to the poor. Remember also, that too high a dose of any metal can be toxic. In fact, selenium – a nutrient with positive effects taken in the proper amounts – has been poisoning wildlife for years in the western United States.

Reducing metal risk

Many countries have laws to control metal emissions, but not all enforce them well. In the United States the law controls metal discharges to water. Air emissions are controlled under the 1990 Clean Air Act Amendments, which mandate the use of best available control technology. More recent EPA regulations are greatly reducing lead, cadmium, and mercury emissions from incinerators of municipal solid waste and medical waste. A joint Canadian–US effort is working to prevent further metal build-up in the Great Lakes. Modern technology, as used in a new smelter-refinery complex in Utah, can help lower metal pollution; it is expected to be among the cleanest of the world's smelters. Using pollution prevention has led to lowered metal pollution in many cases, for example when the printing industry replaced heavy-metal pigments with soy-based ones, or when heavy metals in both paper and plastic packaging were restricted.

Box 15.4 | Fouling ocean-going vessels

Tin is not very toxic. Indeed, elemental tin is often the inner layer in metal food cans, coming in direct contact with food. However, *organotin* chemicals, such as *tributyl tin*, are toxic.

Algae, barnacles, slime, fungi, diatoms, and crustaceans attach themselves to the hulls of ocean-going vessels, slowing speed, increasing fuel use and decreasing maneuverability. In the 1970s, antifouling paints with organotin additives (especially *tributyltin*, TBT) were introduced. Hulls became much cleaner. Unfortunately, water leaches TBT from the paint. ■ Persistence. Released near the water's surface TBT persists only a few days. Microbes can degrade TBT to the less toxic dibutyltin and monobutyltin, but degradation slows if TBT continues to accumulate in sediments. In cold-water sediments, its half-life is over 2 years. ■ Bioaccumulation. TBT bioaccumulates in fat. ■ Toxicity. TBT is exceptionally toxic. Depending on dose and conditions TBT causes high rates of death among mussel larvae, can thicken oyster shells, and causes snail imposex (female snails have a penis). TBT can be toxic to crustaceans at concentrations of less than 1 μg/l. ■ Harbors and marinas are often most polluted with organotin compounds.

■ Reducing risk. Other products in addition to paints may contain organotin – including plastics, sanitary napkins, diapers, cellophane wraps, and dish sponges. Some of these uses can be eliminated, and some countries have already banned or restricted TBTs. In 2001, the 159 member states of the International Maritime Organization voted to restrict persistent organotin additives in paint, but will not entirely ban them until 2008. This will allow time to find substitute biocides that are less environmentally harmful. Alternatives already exist, but none perform as well as TBT.

Question 15.1

1. Why would TBT near the water's surface break down more quickly than that which is buried in sediments?

SECTION II

Four PBT metals

The US EPA ranks metals as among the agents posing the greatest hazard to humans. Four metals – lead, mercury, cadmium, and arsenic – are among the ten most-common pollutants found at US hazardous-waste sites. All four are characterized as PBTs. Each is discussed below.

Lead

Lead concentration in recently formed Antarctic ice is four times greater than in ice formed prior to the industrial age. Its concentration in recent coral shells is 15 times greater than in shells deposited a century ago. Lead concentration in household dusts can be 500 times greater than the background level in the Earth's crust. ■ Lead has wonderful properties. Ductile and easy to work with, lead has been used by humans for thousands of years. However, it was in the twentieth century that lead became ubiquitous in the environment. ■ It was convenient to use, and was widely used in plumbing and soldering. When added to paint, lead protects both indoor and outdoor surfaces. When added to gasoline, tetraethyl lead is an excellent anti-knock agent. Lead print was used in printing newspapers, magazines and books. *Lead found its way into dozens of products*. It was much harder to back off, but step-by-step industrialized countries did remove lead from plumbing, paint, gasoline, print, and many smaller uses. In 2003, its major remaining use is in lead-acid automobile batteries.

Lead's adverse effects

Thousands of years ago ancients knew lead was toxic, and forced slaves to do the mining. It continued to be used for thousands of years. In the late twentieth century, childhood lead poisoning was described as the most consequential environmental health problem in the United States. Lead's effect on the nervous system of the developing fetus and small child is of most concern. The potential for damage starts long before pregnancy. The mother may have been exposed as a child and, because the body treats lead much as it does calcium, ingested lead accumulated in her bones. About 90% of a person's lead intake is eventually stored in the skeleton. Lead levels in modern human skeletons and teeth are hundreds of times greater than those found in pre-industrial-age skeletons. During pregnancy, as the mother's bones release calcium to the blood to meet the needs of her fetus, lead is released too. Lead passes with calcium into the placenta, thus exposing the fetus.

Very-low doses of lead may not obviously harm the fetus or small child. However, it has subtle effects on the nervous system, detected in lowered intelligence quotients (IQs). The average deficit may be only a few points, but one author noted, "On a societal basis, the aggregate loss of cognitive acuity due to lead exposure can be enormous." And for children who would have had a low IQ anyway, a further lowering could shift them into a severe-deficit range. For children with higher exposure to lead and higher than average body burdens, lead is associated with increased distractibility and aggressiveness. One epidemiological study indicated that boys whose bones contained high levels of lead were more likely to be juvenile delinquents. In addition to lead's toxicity to the developing nervous system, lead may cause kidney cancer. Mice exposed to lead *in utero* developed kidney cancer later in their lives.

Although adults are not as sensitive as children, they too suffer adverse effects from lead exposure. Chronic workplace exposure increases the likelihood of high blood pressure, can damage the nervous system and kidneys, and sometimes leads to anemia and infertility. Disturbing results recently emerged: long after worker exposure to lead ceased, damage to brain function continued to worsen. Researchers at Johns Hopkins University followed 535 individuals who had worked with lead for an average of 8 years, but who were unexposed in the subsequent 16 years. They compared them to a control group of 118 unexposed individuals living in the same neighborhood. Lead-exposed workers still showed clear deficits in memory and learning abilities, as compared with controls. Researchers said it was as if lead exposure had aged the workers' brains by 5 years.

Sources of lead and exposure to lead

Lead-emitting sources are similar to those for other metals: mining and smelting, coal-burning electric power plants, and incinerators. *But it is lead that has already been in the environment for many years* that can often pose the most serious exposure. Small children, often poor, may live in poorly maintained older houses containing leaded paint. They inhale leaded dust that is formed as peeling paint crumbles into dust and becomes airborne. Exposure may come too from lead-contaminated soil around older homes where leaded exterior paint flakes off into the soil. Once tracked indoors, the soil may become part of household dust. In addition, toddlers may suck on sweet-tasting leaded paint on windowsills, and so be ingesting as well as inhaling lead. Moreover, poor children may have less than optimal calcium and iron in their diet, and may absorb more of the lead they ingest. Old housing is also more likely to have lead solder in the water pipes, so drinking water can contribute to exposure. ■ *Food* is the highest source of exposure for people living in lead-free or lead-safe homes.

Gasoline and lead in children

Lead is an instance where the United States aggressively and successfully pursued pollution prevention (P^2). ■ Gasoline. Until the mid-1970s, motor-vehicle exhaust was a major source of lead to the US environment and a major source of exposure. After banning lead from gasoline, emissions to air fell more than 90%, and blood levels in US children fell concurrently. Ten micrograms of lead per 100 ml of blood is the threshold of concern. By the mid-1990s, blood lead levels of most children in the critical age range of 1 to 5 years was down to 4 to 6 μg/100 ml. Only 4.3% tested above 10 μg/100 ml. Many developing countries have also recently begun prohibiting the addition of lead to gasoline. This is now happening in China where 65% of children have blood lead levels greater than 10 μg/100 ml. ■ Incinerators. The P^2 measure of banning lead from gasoline is given most credit for lowering body burdens of lead although, in some locales reduced lead emissions from incinerators is considered to have been a factor too. Many developing countries have also recently begun prohibiting the addition of lead to gasoline. This is now happening in China where 65% of children have blood lead levels greater than 10 μg/100 ml.

Other P^2 measures

Over the years, control of incinerator emissions has improved, limiting the emissions of lead and other metals into air. Recent US EPA regulations are reducing emissions another 95% to 99%. In the late 1970s, using lead in paint for domestic purposes was banned. The use of lead to solder drinking-water pipes was also eliminated; so was lead solder for sealing food and soft-drink cans (although some imported cans still have lead solder), and in drinking-water fountains. In the printing industry, soy ink began to replace lead print. Even the soft lead foil used to seal wine bottles was banned.

Products still containing lead

There is no substitute for the lead in motor-vehicle lead-acid batteries and this now is the major use of lead. Many US states require that those batteries are removed from municipal waste before it is incinerated. Ceramics sometimes still contain lead. Ceramics made in industrialized countries are fired at temperatures high enough to prevent lead from leaching into food and drink. However, unless crockery bought in less-developed countries is tested for lead, it is assumed to contain lead.

Workplace exposure

Wealthy countries control lead exposure in the workplace, but jobs involving working with lead have moved to countries with poor protection. Moreover, Mexico, Peru, and other countries often have small "cottage industries." These recycle lead-acid batteries, or add lead glazing to pottery without controls on fume emissions. Adverse effects in these workers include high blood pressure and kidney failure. Children are employed in some of these cottage industries.

Questions 15.2

1. Why is the risk of leaded gasoline so much greater than the risk of lead in lead-acid batteries?

2. (a) Consider the four life-cycle stages of a lead-acid battery. Which could result in the greatest lead *emissions* to the environment? Explain. (b)Which stage might result in the highest *exposure*?
3. An epidemiological study has shown that individuals with high workplace exposure to lead had more than a three-fold increased risk of Alzheimer's disease. What else would you want to know before you decided the link between lead and Alzheimer's was real?

Reducing the risk of lead already present

Lead is a metal that is persistent. It is also pervasive. Many road sides still have high lead soil levels. Leaded paint remains in place for many years. Virtually any US house built before 1980 has some lead paint. Older houses have more. If the leaded-paint walls are covered with wallpaper or wallboard, they can be regarded as *lead safe*. It is harder to remove the risk to small children of dust and crumbled paint from surfaces such as windowsills although it helps to wash these surfaces daily, and vacuum up dust regularly. Away from home, daycare centers are regulated to assure provision of a lead-safe environment. Some municipalities have screening programs to test blood from high-risk small children; that is, those living in deteriorated older homes. Lead in water pipes also remains in place for many years, so the US EPA requires municipalities to maintain drinking-water supplies at a pH alkaline enough to limit the leaching of lead from old pipes. Individuals living in homes that have lead solder in the water pipes can also protect themselves by allowing water from each faucet to run for perhaps 30 seconds every morning to wash out lead leached into the standing water overnight. If water pipes contain lead, it is also important not to use hot water for cooking because hot water leaches more lead from pipes than cold water.

Despite impressive declines in lead contamination, issues remain. Even the 4 to 6 μg/100 ml now found in most US children is hundreds of times greater than the estimated 0.016 μg/100 ml of prehistoric people. ■ In addition, blood levels are still high in many African-American children. As compared with 4% of the US population overall, about 35% of black children living in substandard inner-city housing have lead levels higher than 10 μg/100 ml. This leaves them at risk of adverse effects on behavior and mental abilities. In the United States, if a child's blood level is only slightly above 10 μg/100 ml, the recommended follow-up is to find and reduce sources of lead exposure. Higher levels elicit more aggressive attempts to find the source of lead exposure, and remove it. Medical intervention has sometimes been used to remove lead from children's bodies although it is considered to be of questionable value.

Reducing lead's risk in Mexico

Just south of the US border, a phase out of lead in gasoline only began in 1992; and lead-glazed pottery is still made and used. Investigators found that children in Tijuana, a city on the Mexico–US border, had

Table 15.1 Sources of lead, mercury, and cadmium in US municipal solid waste (in tons)[a,b]

Year	**1986**	**2000**
Lead[c]	213 652	281 887
Lead-acid batteries	138 000	182 000
Consumer electronics	59 000	85 000
Mercury[c]	709	173
Household batteries	621	99
Electric lighting	27	41
Cadmium[c]	1788	2684
Rechargeable batteries	930	2035
Plastics	502	380

[a] 1 ton is equivalent to 0.94 tonnes.

[b] The two largest sources are shown in each case. See Internet resources for US EPA characterization of products containing lead and cadmium.

[c] First row for each metal is the total found in municipal solid waste.

blood lead levels twice those of US children. Moreover, unlike US children, the levels did not decrease, and sometimes increased as the children got older. This was partially attributed to the use of lead-glazed pottery. Investigators doing the study provided information to parents of the children whose lead levels they had measured, showing them how to identify sources of lead and minimize its risk. Children of parents so educated were later tested again. Their blood lead levels had dropped. Investigators concluded that parental education could partially protect children. Limited resources prevented the removal of all sources of lead from their environment, which could have further lowered blood levels. In countries still using leaded gasoline, motor-vehicle exhaust remains a major source of exposure. However, more and more countries are banning leaded gasoline.

Some lead is natural

It is vital to reduce human exposure to lead as much as possible. But remember that lead, like all metals, is a natural element. We cannot totally eliminate it. Alternatives can pose problems too. In gasoline, lead performed the necessary function of an anti-knock agent. When lead was banned, it was replaced by benzene – a known human carcinogen. The amount of benzene in gasoline has also been substantially reduced. Worldwide, more than 60% of the lead remaining in use is in lead-acid batteries, and as the number of motor vehicles grows so does the amount of lead used. Lead used in consumer electronics is also slowly growing (Table 15.1).

Mercury

You have probably heard of "quicksilver," seen mercury in thermometers, and know it is a liquid metal. You may have read too of the "Mad

Hatter" in Lewis Carroll's *Alice in Wonderland*. In Carroll's time, hatters were exposed to mercury vapor from the felting process, and suffered damaged nervous systems. Mercury outgases from many natural sites, but it is human activities that have increased its environmental levels. An unfortunate twist worsens mercury's damage: when mercury is released into the atmosphere, much eventually ends up in water; there it attaches to sediments where certain bacteria, for reasons of their own, convert it to an organometallic, *methylmercury*, a chemical more toxic than elemental mercury. To make matters worse, methylmercury powerfully biomagnifies in the food web, sometimes a million-fold or more compared with its concentration in water. The process of biomagnification is as follows: single-celled algae concentrate the methylmercury; tiny animals (zooplankton such as daphnia) eat the algae; fish eat the daphnia; larger fish eat smaller ones; at each step, methylmercury concentrates further (Figure 3.3). Some game fish have methylmercury concentrations 200 000 times greater than the surrounding water. Fish-eating birds and mammals can accumulate even higher levels. This has led to most US states posting fresh-water-lake advisories warning pregnant women, women of childbearing age, and small children not to eat the fish, or to eat only limited amounts of certain fish.

Mercury's movement around the world

Much of the mercury emitted by fossil-fuel burning facilities is the volatile elemental mercury which, under some circumstances, can remain airborne for a year or two and can travel long distances. It stays airborne so long because emissions of the volatile elemental mercury are as vapor.[3] ■ An illustration of its transport from distant sources is seen in the sediments of isolated lakes in Minnesota, a US state. By analyzing successively deeper sediment layers, and comparing them with more recent layers, scientists found that mercury concentrations had tripled over 150 years. However, these lakes were far from industrial activity meaning that the mercury had to have arrived in the lakes by air transport from distant sources. There were no known natural phenomena to explain the increase. ■ Depending on how wind currents move, some regions end up with more mercury than others. This happens in the northeastern US states and Canada's maritime provinces. This locale, and the fish in its water bodies, suffer from excess mercury carried on wind currents from western regions.

One story with a favorable ending occurred in Florida's Everglades. There, mercury in largemouth bass was often higher than 1.5 ppm. This level made the fish unsafe to eat. Investigation revealed the

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[3] Smaller amounts of mercury are emitted as mercury compounds. Mercury compounds such as mercuric chloride are particulates. As such, they are not volatile, and come to Earth fairly quickly. On the other hand, the vaporous elemental mercury must be converted to a mercury compound or bind to a particulate before it comes back to Earth.

mercury did not arrive from streams feeding into the Everglades. Rather, it came from airborne sources, specifically from Florida incinerators. After these cut their emissions by 99%, the mercury levels in fish also fell. ■ However, solutions are more difficult in many cases. Because mercury travels so extensively and can also arise naturally, its sources are often not identified. Moreover, if the mercury has accumulated for many years in sediment, it can continue its movement into the food web even if emissions are cut. In these cases, it can take many years to decrease mercury levels in the food web.

Mercury sources

Worldwide, between 2700 and 6000 tons (2430 and 5400 tonnes) of mercury a year arise from natural sources. Human activities generate another 2000 to 3000 tons (1800 to 2700 tonnes). Percentage-wise, the amount that humans contribute may not seem great, but remember that a portion is converted to methylmercury and biomagnified. In 1993, the EPA reported that the United States generates about 340 tons (308 tonnes) of airborne mercury each year, with over 80% of that arising from combustion sources. ■ The largest one source is coal-burning power plants although municipal, medical- and hazardous-waste incinerators, and industrial boilers emit mercury too. Residential combustion emits a few tons. ■ An EPA study reported that about 40% of mercury emissions were natural outgassings from oceans, soils, the Earth's crust, and volcanoes.[4]

Mercury-containing products

Products containing mercury can contribute to pollution. These include thermometers, thermostats, blood-pressure cuffs, other mercury measuring devices, electrical switches, batteries, fluorescent lamps, and huge numbers of batteries. Until the early 1990s, mercury was also used as a fungicide in paint, seeds, and golf-course greens. If mercury-containing products such as batteries are incinerated at the end of their lives, emission standards must be met in developed countries. But if the products are landfilled, investigation has revealed a surprising result. The air above landfills contains mercury, including significant amounts of methylmercury; that is, landfills too have the bacteria that convert mercury to methylmercury.

Exposure and adverse effects

About 95% of the average person's mercury exposure comes from eating contaminated fish. See Figure 15.2.

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[4] Some criticized the 40% figure saying that not all of it was natural, but rather represents earlier human emissions that settled back onto land. Re-evaporating from land, it may have been counted as natural. For example, vegetation takes up mercury from air and releases it again. You can begin to see the difficulty of determining what proportion of mercury is natural and how much is human generated. One thing we can certainly say is that mercury's environmental levels did indeed increase for many years in the United States. They are still increasing in some parts of the world.

Mercury (mainly elemental mercury vapor) is emitted to air from human and natural sources.

Mercury is transported by the wind. Eventually, elemental mercury is oxidized to mercury compounds, which are particles and so can wash out with rain, or fall out by gravity.[*]

⇓

If deposited into water mercury[**] binds to sediment. Bacteria transform a portion to methylmercury. Algae and other phytoplankton take up methylmercury.

⇓

Invertebrate animals eat the mercury-containing phytoplankton.
Small fish eat the invertebrate animals; larger fish eat the smaller.
Larger fish accumulate successively more mercury.
Birds, animals, and humans eat the contaminated fish.

[*] Elemental mercury may remain in the atmosphere for as long as two years.

[**] Mercury compounds also fall on soil and vegetation, but conversion to the very toxic methylmercury requires the airless environment of sediment, rice paddy, or the interior of a landfill.

Figure 15.2 Mercury biomagnification in fish and animals

- Prenatal exposure. As with lead, the greatest concern about mercury is its toxicity to the nervous system. Again, as with lead, the fetus and small child bear the greatest risk. The developing embryo is five to ten times more sensitive to mercury than adults. In 2000, the US National Research Council reported that 60 000 US babies born each year are at risk of slowed development, such as delayed walking and talking, because of prenatal methylmercury exposure. Most maternal exposure results from eating contaminated fish.
- Workplace exposure. With the exception of some dental workers, workplace exposures are generally well controlled in developed countries. Unfortunately, facilities making most mercury measuring devices are now located in countries where workers often lack basic protection. Chronic inhalation of elemental mercury fumes over weeks, months, or years leads to poor coordination and strange sensations in fingers, toes, and lips. Hearing and eyesight can be impaired, and a “Mad Hatter” tremor occurs. Severe poisoning can lead to blindness, deafness, kidney damage, irreversible brain damage, even death.
- Wildlife exposure. Think about birds that eat large quantities of fish such as loons and eagles. In Maine, a far-northeastern US state, loons have mercury levels up to 35 ppm, some of the highest levels ever recorded; northeastern US states and Canada’s eastern maritime provinces are “hot spots.” Wind currents carry mercury from coal-burning power plants and incinerators in mid-western states to the northeast. Captive birds with levels of mercury as high as those found in wild loons reproduce poorly; so do eagles that have high levels of mercury in their feathers. It is feared that such birds have poorer physical dexterity and may have more difficulty catching fish or avoiding predators. Wild animals that eat contaminated fish are also at risk.

Box 15.5 Mercury poisoning

Beginning in the 1930s and continuing until the late 1960s, Tokyo's Chisso Corporation routinely discharged elemental mercury into Japan's Minamata Bay. There, bacteria converted some to methylmercury, which built up in the food web. Methylmercury levels in the fish in the bay ranged from 9 to 24 ppm, with some as high as 40 ppm. Unknowing people ate the fish, and as many as 200 000 were poisoned; hundreds died; thousands suffered chronic disease. Chronic, sometimes severe and debilitating, nervous-system damage was seen; so were miscarriages, and deformed fetuses. Victims charged authorities with knowing about the pollution and its health risks, but failing to stop them or inform the public. The poisonings resulted in a bitter lawsuit against Chisso that continued for nearly 30 years. In 1996, 3171 victims finally settled. However, one elderly and still-ill embittered group refused to settle until the government officially apologized to them. The tragedy at Minamata was later eclipsed by other industrial tragedies such as the Bhopal explosion and the *Exxon Valdez* oil spill. But it is to Minamata that a World Bank report pointed, seeing it as a watershed event that brought increased international attention to industrial pollution. After Minamata was publicized, many developing countries set up environmental agencies intending to control pollution, and many of these countries have made progress. More is sorely needed.

Mercury guidelines

Fish in Minamata Bay had mercury levels as high as 40 ppm. Compare these with US Food and Drug Administration (FDA) guidelines.

- FDA considers fish with less than 0.5 ppm mercury safe for human consumption in any amount.
- At 1 ppm, people are advised to limit fish consumption. One ppm is ten times lower than the amount shown to produce adverse effects in adults in the Minamata Bay poisoning.
- Above 1.5 ppm, people are advised not to eat the fish at all.

In 1991, the FDA reported that mercury in most American fish ranged from 0.01 to 0.5 ppm. Exceptions were older, usually larger, ocean fish, e.g., shark, and swordfish, which naturally accumulate mercury to 3 ppm or more. In 2002, both the US FDA and the UK Food Standards Agency issued alerts advising pregnant women, women who may become pregnant, infants, and children under 16 not to eat shark, swordfish, and marlin because of high mercury levels. These are marine species. For fresh water fish, recommendations from the US EPA and state and Canadian province agencies advise those who eat large quantities of fish, such as certain Native Americans to pay special attention to advisories. This is also the case for pregnant, breast-feeding women, those who may become pregnant, and young children. Since 1991, 37 US states have issued health advisories on mercury in fish. Usually state standards are stricter than those of the US FDA. Some state advisories of the 1990s may have arisen not just from testing fish in previously untested lakes and finding increasing mercury levels, but due to a new awareness of mercury's dangers. In 1995, mercury contamination accounted for about two-thirds of all the fish advisories issued in the United States. Other contaminants, on which advisories are still sometimes posted, include dioxins and PCBs.

Reducing mercury's risk

- Using regulations. In the United States, the EPA sets standards for mercury in drinking water, and controls air emissions of mercury. Recent regulations are further reducing mercury emissions. Regulations also control facilities using the mercury-cell process to make chlorine. But only now is the EPA attempting to control the biggest remaining source of mercury emissions, coal-burning power plants. This will be a long, and probably expensive, process.
- Reducing workplace exposure. In the United States, work sites are controlled to greatly limit mercury exposure. Workers in poor countries often remain unprotected. Visitors to China describe toxic reactions among unprotected workers as routine. Workers are simply allowed some time off work to partially recover.
- Reducing or eliminating mercury-containing products. ■ Some US states are working to eliminate mercury-containing products, even fever thermometers. ■ In 1986, the United States used 621 tons (563 tonnes) of mercury in batteries; this declined to 99 tons (90 tonnes) in 2000 (Table 15.1). Only rechargeable batteries and button batteries still contain mercury. One state mandates the removal of button batteries from municipal solid waste before it can be incinerated. ■ Although in smaller amounts than previous years, mercury is still used in fluorescent lights. A goal of the EPA's voluntary Green Lights program is to eliminate mercury use in lighting and, meanwhile, to recycle all spent fluorescent tubes. Some states regulate mercury-containing fluorescent lights as hazardous waste. Despite such actions, mercury use in electric lighting grew from 27 tons (24 tonnes) in 1986 to 41 tons (37 tonnes) in 2000. Researchers are working on fluorescents that contain no mercury. ■ Mercury was once used as a fungicide in paint, but after a child's death resulting from mercury emissions into indoor air, its use in paint was forbidden. ■ Many hospitals did use mercury-containing products. The group, Health Care Without Harm is successfully urging hospitals to phase out the use of such products including blood-pressure cuffs, thermometers, and laboratory chemicals. Another program called "Mad as a Hatter" works to eliminate mercury from research facilities that are under the control of the National Institutes of Health.

Box 15.6 | A mercury quandary

Some human exposure results from minute amounts of mercury vapor emitted within the mouth by amalgams used to fill dental cavities; some contain 50% mercury. Critics of mercury amalgams – used for more than 150 years to fill cavities – claim they are linked to multiple sclerosis, arthritis, mental disorders, and other diseases. People with amalgam fillings do have higher mercury concentrations in their blood than people who don't. However, a 1994 article in a dentistry journal reported that although dentists have a much higher body burden of mercury than the average American, they have no higher incidence of any disease. Also, a study of elderly nuns in Java showed no association between long-term amalgams in teeth, and lowered reasoning ability. The position of the US Public Health Service is that amalgam use should not be regulated unless it is more definitely linked to illness. Rarely, individuals have an amalgam allergy; its symptoms are similar to a skin allergy. Three-quarters of US dentists continue to use silver–mercury amalgams, but the fillings remain controversial. Because other, albeit somewhat more costly, options exist – gold and composite materials – some dentists no longer use mercury amalgams.

Questions 15.3

1. In the United States, several federal agencies evaluated psychological and motor tests done on the babies and small children of island-dwelling peoples who eat large amounts of fish contaminated with methylmercury. The US EPA used this information to set a guideline that is about four times more stringent than the US FDA standard (Box 15.5). The EPA developed its guideline to assist regulators, the people who make decisions ranging from fish consumption advisories to air emissions standards. When the EPA was criticized for its strict standard, it reminded critics that its charge is to protect the most sensitive population, in this case women of childbearing age and small children. A US National Research Council (NRC) report supported the EPA's conclusion: it indicated that 60 000 US babies a year are at risk of slowed development because of prenatal methylmercury exposure. The FDA makes the counterpoint that, if the EPA's guideline stands, it would prevent sales of swordfish, shark, and most tuna. The FDA asks: How can we protect people without scaring them away from a food providing a good source of protein, polyunsaturated fatty acids, and antioxidants, and without needlessly hurting the fishing industry? (a) With which agency do you tend to agree, and what is a possible way to resolve the issue?
2. The US NRC report estimated that 60 000 US babies a year are at risk of slowed development, such as delayed walking and talking, after prenatal exposure to methylmercury. Does this mean that 60 000 babies will be born each year with these adverse effects? Explain.
3. The lowest methylmercury concentration in human blood associated with any observed adverse effect in adults is 200 ppb. The average mercury concentration in American blood is about 8 ppb. (a) Do you believe that 8 ppb is a comfortable margin of safety for adults? Explain (if possible using factor-of-10 concepts from Chapter 4). (b) Would your answer be the same if women of childbearing age had an average of 25 ppb methylmercury in their blood? Explain.
4. Assume you ingested elemental mercury in an amount equivalent to that in a thermometer. What would happen to the ingested mercury? Does your answer explain why elemental mercury is less toxic than methylmercury.
5. Older, larger fish, such as sharks and swordfish, usually have higher mercury concentrations than younger or smaller fish. Why?
6. Mercury concentrates in fish muscle, not fat. Explain if the same techniques used to remove PCBs or dioxins from fish can be used to remove mercury.

7. In 1996, the US Department of Defense (DOD) proposed selling its mercury stockpile, 60% of the world's supply, on the open market. After much public protest, the DOD dropped its proposal. (a) What would be your reaction to such a sale? (b) In Brazil, mercury used in gold mining has resulted in the release of about 170 tons (154 tonnes) of mercury into the environment since 1989. Brazil imports mercury from other countries. Had the DOD sale gone through, part of the stockpile could have been sold to Brazil. Does knowing this affect your viewpoint? (c) Most nations that sell mercury to Brazil restrict the use of mercury within their own borders. Do you believe this raises ethical implications? Explain.

Cadmium

Whereas lead has been mined for at least 4000 years, cadmium was not even discovered until 1817, and has only been heavily mined since the mid-1940s. Environmental cadmium levels are lower than those of lead, and people ordinarily have lower exposure. Nonetheless, cadmium levels in the environment have been increasing, and exposure is hundreds of times greater than in pre-industrial times.

Toxicity

Cadmium bioaccumulates in the kidney. The amount stored increases with age. Kidney damage is the most common chronic effect among those who have suffered high occupational exposure. In some middle-aged or older individuals *not* occupationally exposed, cadmium has concentrated to levels almost as high as those known to affect kidney function. Cadmium may also contribute to kidney stones. It affects calcium metabolism too and exposure can accentuate osteoporosis. A cadmium poisoning occurred some years ago among poor, elderly Japanese women, who were eating rice grown in cadmium-contaminated paddies. They experienced *itai itai* ("pain, pain") disease, characterized by kidney damage and brittle, painful bones (see Questions 3.1). In rodent studies, cadmium showed many dose-dependent effects, including birth defects; it is also a carcinogen.

Cadmium sources

Cadmium is released into the air during mining and smelting of zinc, lead, and copper. Fossil-fuel burning, especially coal, is an ongoing source. Polyphosphate fertilizers and sewage sludge contribute to cadmium build-up in soils. Consumers know it best from nickel–cadmium rechargeable batteries that power small appliances. These "Nicad" batteries are a major source of cadmium in US municipal solid waste.

Routes of exposure

More than 90% of the average non-smoker's exposure to cadmium is from food. Shellfish concentrate cadmium, and can be a major source of exposure for those who eat scallops and oysters. Fish concentrate less cadmium. Liver and kidney concentrate cadmium, and hunters in some locales are advised not to eat the liver or kidney from moose or bear. High soil levels are a special concern because *plants take up cadmium more readily than other metals*. Because tobacco plants effectively concentrate cadmium, smoking a packet of cigarettes a day can double exposure. Adult smokers can absorb more than 90% of inhaled cadmium whereas only about 5% of the cadmium ingested in food is absorbed. Inhalation is also the greatest route of exposure among those with occupational exposure.

Reducing risk

Society controls cadmium in a number of ways. In the United States, drinking-water standards limit exposure to cadmium, and air emissions are controlled by best available technology (BAT). As with lead and mercury, recent EPA regulations are greatly reducing cadmium emissions from municipal-solid-waste and medical-waste incinerators. However, power-plant emissions are not controlled. Large amounts of cadmium are used in Nicad rechargeable batteries, although it is no longer used in disposable batteries. But, as with disposable batteries, rechargeable batteries too are discarded and are a major source of cadmium in solid waste. The amount continues to grow (Table 15.1). Cadmium is also used as a plasticizer in plastics, although in smaller amounts than previously.

Reducing risk in Australia

Cadmium concentrations in Australian soils had grown high enough over the years to be a cause for concern. In 2002, Australia's government decided to reverse this trend for its citizens' sake, and to maintain the "clean and green" image of its exported agricultural products. It tightened the permissible levels of cadmium in foods such as chocolate, peanuts, mollusks, and certain organ meats. In order to meet new food standards, it needed to minimize cadmium additions to soils, and so lowered permissible amounts entering the soil from fertilizers, manures, and sewage sludge. It is also tightening regulations on permissible cadmium levels in the soil.

Arsenic

Arsenic in drinking water is poisoning millions in Asia (Box 10.3). There, according to a public-health authority, it is causing, "the largest mass poisoning of a population in history."

Toxicity and sources of exposure

Arsenic toxicity is described in Box 10.3. Human-generated sources of arsenic include dust emissions from metal smelting, especially the smelting of copper and lead ores, which often contain arsenic. When this dust is captured, it becomes the source of arsenic used in chromated-copper arsenate (CCA)-treated wood (Box 15.7). Before modern pesticides emerged, arsenic was a common weed killer and rat poison. It was stored in homes and outbuildings where, unfortunately, old containers can still be found. In a recent incident in Maine, arsenic taken from an old container was added to coffee drunk by a group of people; one person was killed and others seriously poisoned.

However, although arsenic was used for many hundreds of years as an instrument of murder, it is seldom used for this purpose now because it is easily detected by the forensic scientist.

Natural arsenic sources include volcanic eruptions. Some coals have high arsenic levels, and the arsenic is emitted when the coal is burned. Soils have at least trace amounts. Some soils, such as those in the western United States have higher levels. A few natural mineral springs and other waters contain very high arsenic levels. Unless you live in an area with arsenic-contaminated drinking water, as has become common in some areas of Asia, *food* is your biggest exposure source. This is true because the arsenic naturally present in soil is taken up into plants. Arsenic may be present in seafood at levels considerably higher than in land-grown foods. Fortunately much of the arsenic in food may not be bioavailable.

Box 15.7 Playground arsenic

In earlier years, playground equipment was metal, but was replaced by wood. To lengthen its life, about 98% of wood destined for outdoor use in the United States is impregnated with chromated-copper arsenate (CCA). However, arsenic can leach from CCA-treated wood. The result is that the soil in some children's playgrounds poses an arsenic risk. Some CCA-treated wood structures endure for many years, but at the end of its usefulness, disposing of CCA-treated wood is a problem. If it is mulched, metals can leach out. Burning it can endanger workers unless emissions are carefully controlled. In landfills, arsenic leaching from CCA-treated wood must be captured.

Reducing risk

Sweden, Germany, Vietnam, and Indonesia are among nations banning or restricting CCA-treated wood. In 2002, the US EPA reached an agreement with industry: within 2 years, industry will voluntarily switch from CCA to an alternative preservative for all playground uses, and home uses such as wooden decks and walks. CCA-treated wood will continue to be used in industrial settings – utility poles, dock pilings, and so on. A pending US law suit would require CCA-treated wood manufacturers to clean up contaminated sites. And there is a campaign that encourages schools and communities to test playgrounds for arsenic.

Questions 15.4

1. Individuals in industrialized countries have a cadmium intake of between 10 and 50 μg/day. The EPA recommends an upper limit of 70 μg/day. (a) Think back to the risk-assessment concepts of Chapter 4. Do you believe that 10 to 50 μg provides a comfortable margin of safety? Explain. (b) What else could society do to limit cadmium emissions or exposure? (c) Are there ways to lower your cadmium exposure?
2. Seafood has higher levels of metals such as mercury, cadmium, and arsenic than fresh water fish. Explain how the composition of sea water versus fresh water can explain this.

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Chapter 16

Pesticides

> "Good soil is not just dirt. It is a hive of life, much of it either microscopic or even disgusting to urban eyes because urbanites don't understand the need for the growth and decay of slimy things to sustain life. Good farmers are not just people who dig in the dirt. They are the stewards of healthy soil."
>
> *George B. Pyle, Land Institute, Salina, Kansas*

Pesticide use is among the most controversial of topics. Yet, pesticide use is prevalent. Some individuals believe pesticides are necessary to destroy the enemies of human agriculture and health. Others believe we can use *organic farming* to accomplish these ends without synthetic pesticides. A third group believes pesticides are needed, but recognize their limitations; they work to minimize pesticide use under the rubric of "Integrated Pest Management". There is no simple "right" answer, but we do need answers. Consider this challenge from the authors of the article, Can green chemistry promote sustainable agriculture?[1] "Human population is increasing. Demand for food is rising . . . Environmental impacts are worsening. Taken together, few issues reflect the difficulties of sustainable development more than the problem of controlling pests and increasing food production while protecting the environment and conserving natural resources."

Section I discusses why we use pesticides and who uses them. After briefly addressing three major insecticide families, we consider selective versus broad-spectrum pesticides. **Section II** looks at pesticides as pollutants, as food contaminants, and their effects on non-target species. We also examine the important phenomenon of pesticide resistance. **Section III** asks, how can we reduce pesticide use by using integrated pest management and organic farming? **Section IV** brings

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[1] Hjeresen, D. L. and Gonzales, R. Can green chemistry promote sustainable agriculture? Environmental Science and Technology, **36**(5), March, 2002, 102A–107A.

Table 16.1 Some categories of pesticides

Pesticide[a]	**Pest killed**
Insecticides	Insects
Larvicides	Insect larvae
Fungicides	Fungi growing on plants (or animals)
Herbicides	Plants (weeds)
Fumigants	All life forms
Disinfectants	Microorganisms outside the body

[a] There are also pesticides specific to: mites, algae, birds, snails, slugs, and other mollusks, nematodes, fish, and other organisms.

us to alternative pesticides that are less toxic and less environmentally harmful. **Section V** looks at the special problems posed by pesticide use in impoverished countries. Finally, **Section VI** looks at using biological organisms as pesticides, with an emphasis on bioengineered organisms.

SECTION I

What are pesticides? Why are they used?

Pesticides are agents used to destroy pests. Under certain circumstances almost any living creature can be a pest. The purposes of pesticide use are to increase the production of food and fiber and to promote public health; in practice they are also used for aesthetic reasons. A pesticide that kills insects is an *insecticide*. One killing plants is a *herbicide*. Other pesticide types are seen in Table 16.1. Among the pests attacking agricultural crops are insects, weeds, rodents, birds, and disease-causing organisms including fungi and bacteria. Weeds are undesired plants of any kind that, if left uncontrolled, crowd out the desired crop plant. The amount of manual labor necessary to control weeds without help from herbicides or machines may be difficult to imagine. Well-to-do societies with their abundant food supply also don't ordinarily think of the total loss of a food crop. An example was the devastation of potato crops by a fungal infection in nineteenth-century Ireland. The resulting famine drove millions to immigrate to the United States, and resulted in the death of another million remaining behind. Similar fungal infections are still found in potatoes today, but are controlled using pesticides. Pest infestations have afflicted agriculture for as many thousands of years as humans have farmed. For longer periods yet, pests – including fleas, lice, mosquitoes, flies, roundworms, rats, and mice – have threatened human health.

For thousands of years, people looked for means to rid their crops of the insects eating them, the weeds choking them, or the fungi making them uneatable. People began using the chemical element *sulfur* as a pesticide thousands of years ago; some organic gardeners still use it. Extracts of chrysanthemum flowers containing *pyrethrum* have been used for nearly as long, and tobacco extracts containing *nicotine* have been used for hundreds of years. In the late 1800s, inorganic chemical pesticides containing arsenic, mercury, lead, and copper came into widespread use. An elderly man wrote a letter to a periodical in 1989 describing his grandmother's 1920s gardening chemicals. In addition to occasionally using the highly toxic gas hydrogen cyanide as a fumigant, she used Paris green (copper arsenate), lead arsenate, and nicotine sulfate to control garden pests. Given the widespread use of metal pesticides in the first half of this century, it was not surprising that the first round up of household hazardous waste that Massachusetts carried out in the 1980s, recovered 3 tons (2.7 tonnes) of arsenic chemicals that had lain around in sheds and barns for many years.

These early pesticides were only partially effective. So, when the very effective synthetic insecticide *dichlorodiphenyltrichloroethane* (DDT) was introduced in 1942, farmers and the public-health community quickly embraced it. DDT was lethal to many insects, killing the insects infesting crops, the mosquitoes and flies spreading disease, and other insects, such as body lice. Swiss scientist Paul Hermann Müller discovered its insecticidal properties in 1942. Because DDT effectively killed disease-carrying organisms such as mosquitoes, this was considered a major medical coup, and Müller received the 1948 Nobel Prize for Physiology and Medicine. Many other synthetic chemical pesticides were quickly developed and saw widespread use. Even as early as the 1940s, the ability of insects and other pests to demonstrate resistance to pesticides was observed. However, most pesticides remained effective and resistance caused little concern. DDT and similar organochlorine pesticides showed relatively low acute toxicity to humans, and were not absorbed through the skin. Possible chronic toxicity was little considered. The result was wide and often indiscriminate pesticide use. It was not until the early 1960s that Rachel Carson's famous book, *Silent Spring*, forced Americans to see the darker face of DDT and other pesticides.

Why are pesticides used?

As you read over the reasons that pesticides are used, distinguish between what pesticides *allow* us to do, and whether what they allow is always necessary. An example: many crops could not be grown in ecologically *in*appropriate regions without pesticides; as one instance, strawberries would not grow (as large commercial crops) without pesticides in the warm humid southeastern United States.

Pesticides make it possible to *grow crops at times of year* when they could not otherwise grow because pests would make it impossible. Fruits and vegetables are found at the market year round not only because they can be transported long distances from warmer climates, but because pesticides make it possible to grow them over longer growing seasons. Without fungicides, for example, certain crops could not grow under conditions where fungi proliferate. Many believe that the health advantages of having fresh fruit and vegetables available year round and their lowered cost make up for any health risk that pesticides pose.

Pesticide makes it possible to *grow crops in ecologically inappropriate regions* where they could not otherwise be reliably grown. In such locales, greater quantities of pesticides are often required for successful crops. Cotton, for example, grows well in some parts of Texas with little or no pesticide, whereas in humid southeastern US states the yield is higher, but the crop requires many pesticide applications. Unfortunately, growing a crop in a more appropriate region may not be easy or even possible for established farmers, e.g., when a farmer already has a fruit orchard growing in a region requiring high pesticide use. If we grew crops only in ecologically appropriate locales, it would means lower yields of some crops. It would also mean that some foods would only be seasonally available.

Public-health uses of pesticides include killing *disease-carrying organisms*: mosquitoes, flies, ticks, and rats. Another health-related reason is *reducing the growth of fungi* on crops, fungi that sometimes produce very toxic chemicals; recall the highly toxic aflatoxins (Box 3.3) Pesticides also make it possible to *store food products* for long periods. After harvest, grain is fumigated to kill insects and other infesting organisms that could otherwise multiply during storage destroying grain or making it inedible. For similar reasons, crops are fumigated before being transported long distances to market.

Pesticides are often used for *aesthetic reasons*. People growing up in an age of pesticides expect perfect fruits and vegetables. Many blemishes on fruit and vegetables caused by insects may not harm the produce, but people won't buy blemished fruit – even fruits such as oranges, which are peeled anyway. Although caterpillars on broccoli can be washed away, people wouldn't buy broccoli with caterpillars on it; or, 50 years ago, a worm in an apple was something to pare from the apple, not a reason to throw it away. Golfing greens are kept looking perfect using pesticides, although historically golf was played on imperfect greens.

Pesticides make *monocultures* possible. In a monoculture, large tracts of land are devoted to only one crop such as wheat, cotton, soybeans, or corn, season after season. Without pesticides, pests of that crop would build up to a point where the crop could no longer be grown at that location. In fact, monocultures were not possible before the 1940s when effective and inexpensive pesticides became available. Monoculture crops are farmed using heavy machinery leading to soil compaction. Soil quality is further worsened because neither pesticides nor synthetic fertilizers provide organic material to the soil as is the case with manure and compost. Lack of organic matter makes the soil inhospitable to the worms and microorganisms needed for good soil fertility. Fields planted in row-crop monocultures are prone to soil erosion and to runoff of fertilizer and pesticide applications. And monocultures – by definition – do not support biodiversity, but rather the opposite. University of Maine entomologist Dr. Randall Alford spoke of entering cotton fields in the southern United States when he was a student and being struck by the stillness, the awareness that he and the cotton plants were probably the only living creatures. Intensive pesticide application had, for a time, destroyed essentially all other life. At one point, when he entered a field not posted as having been recently treated with organophosphate pesticide, he became very ill with sweating, trembling, and tunnel vision.

Who uses pesticides?

Perhaps a more accurate question would be who does not use pesticides? The surprise is how few people don't.

- Farmers use pesticides to control pests on their crops. They are the largest users of pesticides. They use especially large amounts of herbicides, which account for half of the total volume of pesticide use in the United States. Farmers use lower amounts of insecticides and fungicides and on significantly fewer acres (Figure 16.1).
- Public-health officials control rats, insects or other pests in the community that carry disease or present other dangers.
- Foresters kill invasions of insects or other pests.
- Utility owners keep rights-of-way clear using pesticides.
- Golf-course owners maintain weed-free greens.
- Businesses maintain their premises free of insects, mold, and other pests.
- Industry controls mold and algae that would otherwise grow in their processes.
- Homeowners might kill hornets in a nest too close to the home, unwanted dandelions, garden slugs or insects, house flies, cockroaches, ants, moths, rodents, mildew in a damp bathroom, or a pet's fleas.

Box 16.1 | Disinfectants

Disinfectants (antiseptics or germicides) are used to kill disease-carrying microorganisms found outside the body. Most are non-selective or broad spectrum; that is, when used to wash a surface, the disinfectant destroys all microbes there, not just pathogens. Disinfectants have been used since 1867, when Lister began using phenol to disinfect operating rooms in France. Chemicals related to phenol, such as those found in *Lysol*, are still widely used. Other common disinfectants used in home and industry are chlorine-containing compounds such as sodium hypochlorite (common household bleach).[2] For certain purposes, disinfection is carried out by heat or ionizing radiation.

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[2] Antibiotics do have external uses, e.g., on the skin. However, they are typically taken *internally* by humans or animals to kill pathogenic microorganisms. Antibiotics are not considered pesticides. They are regulated by the Food and Drug Administration not the US EPA.

Figure 16.1 Pesticide being applied by worker in protective suit. Source: US EPA Library of Environmental Images

Regulating pesticides

The law regulating pesticides in the United States is the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) administered by the EPA. The FIFRA regulates the *active* ingredients in pesticide products; that is, the ingredients that actually kill the pest. The FIFRA mandates that pesticide risks be balanced with their benefits. The FIFRA does not regulate the inert ingredients in pesticide preparations, although these often make up the majority of the product and could have adverse effects. The purpose of inert ingredients is to make the active ingredient soluble, to stabilize it, or to allow it to be applied in a specific way.

Insecticide categories

There are many types of pests, and, not surprisingly, many types of pesticides developed to fight them. Only three well-known insecticide categories are mentioned here.

Polychlorinated insecticides

DDT is the best-known organochlorine pesticide. It exerts its toxic effect by acting on nerve membranes to prevent normal conduction of nervous impulses. Lindane, aldrin, and heptachlor are other polychlorinated insecticides also once widely used. Like DDT, most polychlorinated pesticides have been banned, or their use greatly restricted in developed countries because of their environmental persistence, damage to animal populations, and ability to bioaccumulate in animal fat. Both microorganisms and animals find them difficult to degrade. Direct sunlight can destroy them, but they are often trapped in sediments or other locations without exposure. Over its 30 years of use, DDT accumulated in many locations, including the Great Lakes region of the United States. Given time, polychlorinated chemicals do break down, and, 20 years after banning DDT, its environmental levels had dramatically declined in the Great Lakes area, as had its level in fish and in the blood, breast milk, and tissues of humans eating the fish. Nonetheless, DDT remains detectable and will be for years to come.

Other defining characteristics of organochlorine pesticides are low solubility in water and high solubility in lipid materials, including animal fat – where they bioaccumulate. Fortunately, they have low water solubility, and cling to soil particles. Thus, they have little tendency to dissolve in rainwater and migrate into water bodies or groundwater. Another aspect of the behavior of polychlorinated chemicals, described earlier in Chapter 1, is their ability to reach the Arctic via a grasshopper effect; once there, extreme cold prevents their degradation.

Organophosphate insecticides

These came into wide use as highly chlorinated pesticides were being banned. Organophosphates are also toxic to the nervous system of insects, inhibiting the action of the enzyme that breaks down the neurotransmitter acetylcholine; as acetylcholine levels build up, nerves fire uncontrollably. Organophosphates are more acutely toxic than organochlorine pesticides, sometimes much more so. Whereas DDT, for example, has an LD_{50} of 113 mg/kg in rats, the LD_{50} of the organophosphate insecticide *parathion* is 3.6 mg/kg in male rats. (The LD_{50} is the dose killing 50% of animals exposed to it.) Some organophosphate pesticides – again consider parathion – are absorbed across the skin, greatly increasing the danger to pesticide applicators. Most acute, human pesticide poisonings are caused by organophosphate pesticides. In fact, these insecticides are chemical relatives of the exceedingly toxic organophosphate nerve gases. Despite their toxicity, organophosphates were more attractive than organochlorines because they have much shorter lives in the environment and, as they are not fat soluble, they don't bioaccumulate to high levels in fat. However, this implies increased water solubility; thus, after application to a field, rainwater can carry the organophosphates into water bodies or they can percolate down into groundwater.

Carbamate insecticides

A few carbamates are exceptionally toxic, but most are less acutely toxic than the organophosphate pesticides. They exert toxicity in a manner similar to organophosphates, but their effects last for a shorter time. Like the organophosphates, they are short-lived in the environment. Because of their lower toxicity, they are often found in products used by homeowners but are less useful to farmers.

Questions 16.1

1. (a) For what purposes would you consider using a pesticide in your home, yard, or garden? (b) Are there uses of pesticides that you consider trivial?
2. Recall and describe, if you can, a television advertisement for pesticides.

3. To willingly buy discolored or less-attractive fruits and vegetables, you would probably have to overcome certain preconceived notions. What types of blemished produce would you avoid buying?
4. By the late 1990s, humans used more than 5 billion lbs (2.3 billion kg) yearly of pesticides worldwide. Nonetheless, about one-third of crops are lost to pests (insects, weeds, and plant diseases) – about the same as in 1945. Does this mean that pesticides are ineffective or that humans are harvesting no more crops now than in 1940? Explain.

How pesticides kill

You just saw that the three major families of insecticides are all toxic to the nervous system. Other insecticides kill in various ways. For example, *rotenone,* a botanical insecticide (derived from plants) is a stomach and contact poison. *Herbicides* used to kill plants, fall into many groups based on their chemistry and how they kill weeds. Some interfere with the normal function of plant cell membranes, others act on plant metabolism to cause abnormal growth, and still others inhibit the action of enzymes necessary to plant life. Other pesticides exert their toxicity by a variety of mechanisms.

Selective versus broad-spectrum pesticides

Selective and *broad-spectrum* pesticides have a differing potential to do damage. A selective pesticide acts against a limited group of organisms, affecting some aspect of metabolism specific to a limited number of species. Although any chemical is toxic in high doses, a herbicide that interacts only with a plant enzyme is less likely to harm animals, birds, and humans. However, human agriculture is affected by approximately 80 000 plant diseases, 30 000 weeds, and 10 000 insect pests. Thus, except for the more important pests, one cannot expect to find selective means of dealing with each pest. Thus, broader-spectrum pesticides are used and it is they that present greater dangers to non-target species. *Fumigants* present the worst case. Hydrogen cyanide and methyl bromide are fumigants that affect biochemical respiration in many species. Indeed a fumigant is deliberately used to kill many pests at once, those infesting the grain stored in an elevator or a greenhouse, for example. Fumigants are also used to sterilize soil or seeds. They are often gases that can penetrate an enclosed space to do the job required of them. Great care must be taken to protect humans from fumigants because they are also deadly to people.

Other than fumigants, pesticides, although not as selective as we would desire, are intended to kill specific pest categories with minimal toxic effects on humans and other non-target species. However, both wildlife and humans are at risk. Recall from Chapter 2 that worker exposure to chemicals in industry and agriculture is rated a high-priority environmental health risk. In developed countries, most workers are trained in safety techniques. Yet field workers that mix, load, and apply pesticides remain among those at highest risk; they may inhale the pesticides or sometimes absorb them through the

Figure 16.2 Pesticide being sprayed by plane. Source: US EPA Library of Environmental Images

skin. Landowners may not properly educate temporary migrant laborers. Even well-trained workers may become casual and not use protective clothing and equipment properly, especially in hot weather. Workers entering treated areas too soon after pesticide application are at high risk. Drinking water is, at least in the United States an insignificant risk (see Box 4.3). Nonetheless, pesticides are detected in groundwater in many industrialized countries, and without precautions, that contamination could increase. Another source of exposure, i.e., food consumption, is discussed below.

SECTION II

Pesticides as pollutants

Almost all pesticides can become pollutants because of the way they are applied, often by aerial spraying (Figure 16.2). There are some cases in which contamination is not a problem; the pesticide may swiftly degrade into innocuous products, it may not be very mobile and thus not reach water, and it may have low toxicity to non-target organisms. Unfortunately, in most cases, pesticide contamination is a concern.

Pesticide movement in the environment

Herbicides and insecticides are applied over large areas of agricultural fields and forests. Farmers may apply them a dozen times or more during a growing season. Less than half of the applied pesticide actually reaches the insect, weed, or other pest. Most becomes a pollutant. Pesticides applied by spraying will drift with air currents from the point of application. The largest amounts settle onto land and water close to the point of application, but smaller amounts, swept higher into the atmosphere with the winds, can be carried many miles. Pesticides are detected in rainwater. The heavily used herbicide *atrazine* has been found at levels above 1 ppb in rainwater. Certain polychlorinated pesticides detected in wilderness lakes in the northern United States or Canada are not used in these countries and are assumed to have been blown north from Mexico or other Latin American countries. Soil or water, once contaminated with persistent pesticides may remain so for many years, especially in northern locations, where cold weather and lack of intense sunlight prevent them from degrading.

Remember from Chapter 9 that agricultural lands are major sources of non-point-source water pollution. Pesticides also run off from municipal streets and grounds, areas sprayed by utilities, golf-course greens, and homeowners' yards and gardens. Most surface-water pesticide contamination results from runoff from lands to which pesticides have been applied. One study of waters in the Mississippi River basin detected more than 40 pesticides. Atrazine is the most heavily used herbicide in the United States, used especially on corn; it was found in 95% of the samples. In localized areas, atrazine in surface water (not drinking water) exceeds the EPA's maximum contaminant level for drinking water. A number of European countries have banned atrazine.

Questions 16.2

1. Velpar (hexazinone) is a herbicide used on Maine's blueberry barrens. In 1995, after 10 years of use, Velpar was detected in the groundwater of locales where it is used, at an average concentration of 5 ppb. The drinking water of one school had less than 2 ppb, but members of the school board decided to install a filter to remove it. Some individuals want to forbid blueberry growers from continuing to use Velpar. The EPA's health-based limit for this herbicide is 210 ppb. (a) Knowing this, would you be concerned about 2 ppb in water that you personally drink? (b) Would you feel the same if 2 ppb were in water drunk by your child? (c) Do you believe that pesticides found to migrate into groundwater should be banned, or restrictions placed on their use? Explain. (d) Assume that current levels of Velpar do not concern you. Would you nonetheless support continued groundwater monitoring? Why?
2. Long-term use of Velpar or other herbicides leads to loss of organic material from soil. (a) Why does the soil lose organic material? (b) Why is loss of organic matter a concern?

Animal and human exposure

Effects on non-target species

Pesticide applicators and those around them are the ones most likely to have high exposures. Birds, other animals, and beneficial insects are also more highly exposed, and often suffer adverse effects or die.

- Pollinating insects. Consider the importance of pollinating insects to successful crops. Yet, in California, an estimated 11% of honeybee colonies are lost each year to pesticide exposure. Responsible applicators take care to minimize exposure to desirable insects by carefully choosing the pesticides used, not applying them during the blossoming period, choosing to spray in the early morning or the evening when pollinating insects are absent, and using ground applications not aerial spraying to lessen the pesticide drift that could harm nearby colonies.

- Birds. Cornell University has estimated that in the United States alone, at least 67 million birds die each year from pesticide poisoning. Birds die as a direct result from pesticide exposure or from eating pesticide-treated seeds, foliage, or insects; or if they are raptors through eating poisoned prey. On the US east coast, the deaths of as many as 2 million birds in one incident were associated with *carbofuran*, an insecticide, which is also extremely toxic to humans. When applied in a granular form, birds mistake it for dietary grit, eat it, and die. Carbofuran is now restricted or banned in many locales. In a tragic incident on the Argentine Pampas, nearly 6000 migrating Swainson's hawks died from exposure to the pesticide *monocrotophos*. The Argentine government later banned this pesticide. A great many reported bird kills result from homeowners' misuse of pesticides. On average, US homeowners use more than three times as much pesticide per amount of land as do farmers. *Poisonings associated with pesticide use continue to occur*.
- Fish. Fish have died by the thousands or, in some cases by the millions, along with other aquatic species. Deaths are attributed to pesticide runoff or to pesticide drift settling onto water.
- Amphibians. An alarming trend is the disappearance, or reduced populations worldwide, of frogs and other amphibians. Amphibians have thin skins making them especially vulnerable to outside agents. Some see the loss of amphibians as the "canary in the mine" reminding humans that they too may be at peril. Many factors appear implicated in amphibian decline – the continuing loss of habitat is a major factor – but organophosphate-pesticide exposure is believed to be important in at least some cases.

Pesticides in water

Water-soluble pesticides can move down through soil to groundwater. The organochlorine pesticides are much-less water soluble; they cling to soil particles and are less likely to contaminate groundwater. An EPA study found that 10% of American community drinking-water wells and 4% of rural wells contained detectable – not necessarily significant – amounts of at least one pesticide. Groundwater contamination presents special concerns because even pesticides that are short lived in surface water may degrade very slowly in groundwater. Groundwater is also much harder to clean up. Recall that municipal drinking water, whether from groundwater or surface water, is tested for a variety of pollutants, including a number of pesticides. The water must be treated if a contaminant is found above its maximum contaminant level. Because of this practice, significant human exposure is less likely to occur through municipal drinking-water systems. Private well owners, however, are not required to test.

Consumer exposure to pesticide residues on food

Legally, a specific pesticide, can be applied only to certain crops. For each pesticide, and each crop on which it is used, the United States places a legal limit on the residue that can remain on the crop after harvest. This *tolerance* must present a "reasonable certainty of no harm." The crop cannot be legally harvested until a specified number of days after the last application; this allows time for the pesticide to decay to a level below its set tolerance. The length of time varies with each pesticide and crop.[3]

Before a new pesticide can be marketed it must undergo a lengthy and expensive registration process. It undergoes chemical studies and passes many toxicity tests (chronic as well as acute), and studies of its potential effects on wildlife and the environment. The process can take 9 years or longer, and few pesticide candidates make it through to approval. The situation became stricter still in 1996. At that time the US Congress passed the Food Quality Protection Act (FQPA) under which the EPA reassesses all previous tolerances. For foods commonly eaten by children, the EPA must take a new step as it sets tolerances: unless there is strong scientific evidence to indicate otherwise, it must use safety factors ten times more strict than those considered safe for adults.[4] The EPA must also consider the cumulative effect of all exposures to pesticides: food, water, and other sources (Box 4.3). A final FQPA requirement is that the EPA must assess whether a pesticide is likely to be an endocrine disrupter. As of late 2002, most of these requirements are fulfilled. This has happened despite bitter controversy between pesticide producers worrying that their pesticides would be banned and those who do want to see more pesticides banned.

Only a small percentage of all fresh produce can be checked by the US FDA for pesticide residues that may exceed tolerances. Most of the more than 40 fruits and vegetables on the market go unexamined. Other statistics are more reassuring. One is that, when produce is tested only a tiny percentage has residue levels above tolerances, and much is well below. Another reassurance is that the produce samples that the FDA test are raw, unpeeled, unwashed, and fresh from the field. This is an important point because such produce represents a worst case picture of pesticide residue levels. Pesticides continue to

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[3] There are cases in which farmers have inadvertently, or deliberately, mishandled a pesticide by applying it to a crop for which it was not registered, or harvesting the crop too soon after pesticide application. In one notorious case in 1985, aldicarb – one of the most toxic pesticides in use – was illegally applied to watermelons in several western states and British Columbia. More than 1000 people became ill after eating the melons. Fortunately, such incidents are rare.

[4] Children, on a per pound basis, may eat as much as seven times more apples, bananas, grapes, pears, and carrots as adults. Efforts are being made to reduce children's pesticide exposure not only on foods, but in other settings too, especially in schools.

degrade after the produce has been picked, as it goes to market, and up to the time that the food is eaten. Peeling or removing outer leaves removes more residues and cooking the food degrades yet more. Less reassuring is the fact that most food imports into the United States and other countries remain unchecked. It is really impossible to do pesticide analyses on more than a tiny proportion of imported foods.

Regardless of the EPA's careful reassessment and the FDA's food analyses, many people remain concerned about pesticide residues on food, so much so that the sale of organic produce (see description of organic farming below) continues to grow steadily. In North American and European countries, and Japan, the sale of produce that is grown without synthetic pesticides continues to grow by 20% or more a year. This is happening even though organic produce is more expensive.

Effects of pesticides on pest populations

Secondary pests and pest resurgence

■ The pest that a farmer wants to kill, the *primary pest*, may ordinarily hold down the population of a potential pest, the *secondary pest*. If the primary pest is killed, the secondary pest, freed of its enemy, undergoes population growth, until it becomes a pest itself. ■ Pesticides may kill the natural predators of the primary pest. So, when pest survivors reproduce, their population rebounds because the predator previously helping to control it is gone or reduced; that is, there is *pest resurgence*.

Pest resistance

Resistance is a major pesticide-use problem. One or more individuals in the target population of insects, plants, or other pests may have a genetic mutation that permits them to tolerate the pesticide. When the resistant individuals reproduce, they pass resistance genes to their offspring. Over time, the resistant population increases until few individuals susceptible to the pesticide are left. Often, when applicators meet resistance they respond by applying larger quantities of pesticide. This allows the pest to express resistance to the higher doses too. Or, if the applicator switches to a different pesticide, resistance develops to that as well. Because some pest species reproduce very quickly and in huge numbers, resistance can sometimes develop rapidly. Insect resistance has appeared in as little as 5 years in some instances.[5]

About 535 insect and mite species, 210 weed species and 210 plant diseases now resist one or more pesticides. These numbers are growing and some weeds resist all known pesticides. One entomologist

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[5] Part of the problem may be that crop breeders over the years based their work almost entirely on selecting offspring that had enhanced yields. They ignored, or were unaware of, resistance genes that help plants naturally fight off pests, and many resistance genes were lost. Curiously, genetic engineering is used now to introduce genes, albeit from a different species, to help resist pests.

said, “We’re about a half step ahead of the insects, and only a little more than that for weeds and plant diseases.” Insects have inhabited Earth for several hundred million years, plants and microbes for much longer still. They have adapted to ever-changing sometimes dramatically different circumstances. Man-made chemicals are but one more challenge. Consider the *Anopheles* mosquito that carries the malaria parasite. Worldwide, 2.4 billion people live in locales where they could contract malaria, which causes about 3 million deaths a year. DDT and other pesticides once killed *Anopheles* mosquitoes easily, and the possibility seemed real that malaria could be wiped out. Now, the mosquitoes are increasingly resistant; and in some places the incidence of malaria is higher than before pesticides were introduced. The process of pests developing resistance to pesticides is entirely analogous to microorganisms developing resistance to antibiotic drugs. In the case of antibiotics, this situation has become so serious that physicians now worry about a post-antibiotic age. For pesticides too, as increasing numbers of pest species become resistant, many agricultural scientists worry whether effective and relatively safe new pesticides can be developed fast enough to cope with them.

Questions 16.3

1. Consider the benefits and risks of pesticide use. What pesticide uses do you consider most justifiable? Why?
2. (a) If you could eliminate *one* use of pesticides, what would it be? (b) What would be the consequences of eliminating this use?
3. Do you believe the increased food production seen over the past 50 years is sustainable over the long term? Explain.

SECTION III

Reducing pesticide use by changing farming

There are three basic ways of using pesticides. *Conventional farmers* use synthetic pesticides and commonly use them according to a predetermined calendar schedule rather than on the basis of a known need for a pesticide. *Organic farmers* use no synthetic pesticides at all. A third approach is used by farmers using *integrated pest management* (IPM). They use synthetic pesticides, but their philosophy is to manage, not eliminate, pests; this approach limits the circumstances when pesticides are used, the amount used, and the toxicity of the pesticides used.

Organic farming

Organic farmers farm without synthetic pesticides or synthetic fertilizers. ■ They use only “natural” pesticides, such as low-toxicity *Bacillus thuringiensis* (Bt) a microbial insecticide, or occasionally, a copper fungicide. Even these are used in limited amounts for fear of developing pest resistance. They prefer to control pests by intercropping, crop rotation, and other methods described below. ■ They don't use synthetic fertilizers either; nor do they use sewage sludge because it often has extraneous components. They do use manure and compost as fertilizers or grow legumes in rotation with regular crops (the legumes provide both nitrogen nutrients to the soil and condition the soil by providing organic matter). ■ Organic farmers don't use, and oppose the use of, genetically engineered organisms.

Critics of organic agriculture hold that on a given land area, yields cannot match those of pesticide–fertilizer-aided agriculture. In 2002, Swiss researchers published a study in *Science*.[6] They had over a 21-year period carefully compared conventional plots using synthetic fertilizers and synthetic pesticides, with organic plots receiving only manure as fertilizer and occasionally treated with a copper fungicide. They grew identical crops of potatoes, winter wheat, grass–clover, barley, and beets. They used the same crop rotation and tillage practices in both types of plots. Average crop yields were 20% lower with organic farming, but it was more efficient overall. This can be explained as follows. The organic yields were obtained with 50% less nutrient input, and 20% to 56% (depending on the particular crop) less energy use. This takes into account all energy used, including that necessary to manufacture fertilizers and pesticides. The soils of the organic plots were more fertile and supported greater biodiversity – from microorganisms to insects, weeds, and animals. The soil in the conventional plots was inferior, e.g., it formed crusts after a rain. Pesticide manufacturers criticized the study, saying: "There is no mention, nor measure, of the human labor involved in the respective farming systems, the comparative quality of crops harvested, nor the potential benefits for organic plots of pest suppression in adjacent conventional plots." They complained that, "This research was commenced, conducted, and concluded with a predetermined outcome: that organic farming is better."

Another study[7] was carried out over a 15-year period by the non-profit Rodale Institute, which promotes sustainable agriculture. Researchers found that corn and soybean yields were as high with organic farming as they were for conventional farming, and soil fertility was improved. The Rodale and the Swiss studies were done systematically and carefully. However, organic agriculture has not received nearly so much research funding as conventional agriculture. Thus, its potential is not fully known. In impoverished countries, where pesticides are often dangerous and often used unsafely, organic farming and IPM may hold the key to safer farming. The UN

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[6] Mäder, P. Fliebach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. Soil Fertility and biodiversity in organic farming. *Science*, **296**(5573), 31 May, 2002, 1694–1697.

[7] The Rodale Institute. 2002. Farming Systems Trials: The First 15 years. http://www.rodaleinstitute.org/bookstore/products/farm_books/main.shtml (accessed January, 2004).

Food and Agriculture Organization promotes the use of IPM and also urges farmers to remember techniques for managing pests that they learned from their ancestors.

Integrated pest management (IPM)

IPM farmers do use synthetic pesticides, but with a different philosophy: *a major tenet of IPM is to manage pests, not eradicate them*. IPM farmers assess their fields and identify what pests are present. They check for signs that a pest is beginning to reach a stage where it can cause significant damage. Only then is pesticide applied – there is no schedule. Depending on the particular crop and the circumstances under which it is grown, IPM can reduce pesticide use by 50% to 70%. Critics say that sometimes pest populations can inflict damage too rapidly for an inspection regime to work. Other tactics that some IPM farmers use, follow: ■ Choose pesticides with low toxicity to humans and other non-target organisms when they are available. ■ Apply the pesticide in the lowest quantity that can do the job. ■ Make changes in other farming methods that could reduce pesticide use.

Box 16.2 | For IPM to be workable

Farmers must understand the crops they grow, the pests that infest them, and how climatic conditions affect both crops and pests. They must also make the effort to use their knowledge to find less-toxic pesticides and use them safely.

Techniques used by organic farmers and some IPM farmers

The organic farming and IPM toolbox goes beyond considerations of pesticide use. There are many possible tools. Some well-known ones follow.

- Grow crops in ecologically appropriate regions. This would be locales that require the least pesticide for successful crops. This could greatly reduce pesticide use. However, many would resist this change because we now are so accustomed to growing crops almost anywhere.
- Control weeds mechanically. Weeds are destroyed with hand tools or farm machinery and not with herbicides, where possible. This reduces herbicide use but requires more energy use, human or machinery.
- Crop rotation. The crops grown at a given place are varied from season to season or year to year. This controls pests that cannot long survive without a specific crop present. Corn illustrates the value of rotation. Corn root-worm survives over the winter, living to damage or destroy corn if it is replanted in the same place again. To rotate the crop, corn could be planted one year and soybeans the next, greatly reducing the amount of pesticide needed. Rotation has another advantage if legumes are planted as part of the rotation; they replenish soil nitrogen and organic matter so, when the

alternate crop is grown, less pesticide and less fertilizer are needed. However, many farmers grow large tracts of monoculture corn, cotton, wheat, or other crops, and would find rotation impracticable or expensive.

- Intercropping. Growing more than one crop on the land at the same time is another technique to lower pesticide dependence. Again, some farmers growing monoculture crops may not find intercropping reasonable, especially as it involves more labor.
- Eliminate pest breeding places. Do this by destroying crop residues after harvest. Otherwise, pests may survive to attack the following season or year.
- Careful choice of growing season. When possible, plant a crop at a season that minimizes its exposure to pests that can damage or destroy it.
- Biological control. See below.

Biological control (biocontrol)

■ Help may be sought from a natural enemy of the pest, a pest of the pest. This can be a parasitic insect that preys on the pest, or a microorganism that causes a disease in the pest. Well-known examples of insect predators are praying mantises and ladybugs. Ladybugs are reared in large numbers and released to infested areas, where they, at least temporarily, reduce insect populations. Sometimes an *exotic* enemy is, after careful consideration imported from a distant location (Box 16.3). Biocontrol cannot fully replace pesticides. For example, introduced parasites partially control the alfalfa weevil, but some pesticide is still needed. ■ Other forms of biocontrol: (1) Large numbers of a pest's eggs are hatched, raised to adulthood, sterilized, and released. The sterilized pests mate with normal insects, but with no offspring produced, there are fewer pests. (2) Ensure that enough habitat exists to allow a pest's natural enemies to grow.

Box 16.3 | Importing biocontrol agents

■ An early instance of this occurred in the nineteenth century, when the *cottony-cushion scale* threatened the Californian citrus industry. This pest was not an American insect, but had been introduced from Australia. Australian entomologists identified two enemies of the scale and, in the late 1880s, took them to California. Within a few months the scale was brought under control, and has remained so. ■ Nearly a hundred years later, cassava plant roots (a basic food for millions in Africa) were infested by the *cassava mealybug*, an insect that grows entirely on cassava. In heavily infested fields, farmers lost up to 80% of their crop. Detective work revealed that the mealybug was not African, but was from South America, the same continent from which cassava came. Subsequently, a wasp, *Epidinocarsis lopezi*, a natural enemy of the mealybug, was identified in South America. After careful study, the wasp was introduced into African cassava fields. Once it was clear that the wasp effectively killed mealybugs, researchers bred it in large numbers and distributed it over the large region of Africa affected by the mealybug.

A major concern

Introducing an exotic insect – from another region or country – may allow the exotic insect to become a pest as it may have no enemies in its new setting. This is why the South American wasp was carefully studied before it was introduced into Africa to control the mealybug. However, an insect that preys on other insects has a fortunate characteristic. It usually preys only on those species with which it evolved. Because it attacks only the pest it was introduced to control, the concern associated with introducing an exotic species is reduced.

Other examples

The Californian and African examples given here are not isolated instances. In more than 160 countries, about 560 biological control agents have been introduced against nearly 300 target insect pests. Substantial or complete pest control resulted. Professor L. E. Ehler of the University of California at Davis points out that this remedy does not have the toxic side effects of chemical pesticides and is often permanent and economical. Not just insects, but weeds and other pests can be biologically controlled too. As with insects, many weeds infesting US crops are exotics. To control an exotic weed, researchers go to its original home to find an insect or pathogenic microorganism that can control it. As with insects, a weed enemy must be carefully studied to minimize the chance that it will itself become a pest.

Sustainable agriculture

IPM and organic farming are often considered key to sustainable agriculture. However, the criticism that they may not produce as much food as conventional agriculture is worrisome because human populations continue to grow. On the other hand, many doubt that high-input agriculture (high inputs of energy, pesticides, fertilizers, water, and expensive machinery) is sustainable. Here is where supporters of transgenic plants (see below) make their arguments – that thoughtful use of genetically modified organisms may have much to offer the impoverished world.

Questions 16.4

1. Growing crops such as cotton, fruit or other produce in ecologically "inappropriate" regions means using much more pesticide. However, growing them only in ecologically appropriate regions could mean a lower crop yield. (a) Do you think this is an important enough reason to grow crops in ecologically inappropriate regions? Explain. (b) How important is it to you personally that produce be available at any time of year?
2. A product not available all year round in your own State or country could be grown in an ecologically appropriate region elsewhere, and trucked, shipped, or flown in from other parts of the world. (a) What are the environmental consequences of transporting agricultural or other goods long distances to market? (b) If you had to choose which crops to import long distances, which would you choose? Explain.

3. Some believe that modern high-input agriculture is not sustainable. (a) What are the reasons to believe this? (b) Do you believe that IPM can be sustainable? Explain.

SECTION IV

Searching for alternative pesticides

Sometimes less-toxic pesticides are available to farmers, but they may not have the knowledge to use them or they may cost more. In recent years, chemical companies have emphasized the development of pesticides that are less toxic to non-target species and to the environment, and that work at much lower concentrations. Some new herbicides are effective when applied at 0.02 lb/acre (22 g/ha). Compare this with the more typical 2 lb/acre (2.2 kg/ha) for older herbicides. See Table 16.2 for traits that are desirable in a pesticide.

Controlling a pest with the pest's own chemicals

One example is *pheromones*, chemicals produced by female insects to attract males. The pheromone is used to attract males into a trap. Another example is insect *growth regulators*, chemicals that control stages of their life cycle. The growth regulator is sprayed on a crop infested with that insect's larvae and interferes with larval development into adults. ■ Notice that the chemist's handiwork is necessary for pheromones or growth regulators to work. A pheromone or growth regulator must first be purified from the insect and its structure elucidated. Then, because such tiny amounts of these chemicals are produced by the insects themselves, the chemicals must be synthesized to provide quantities large enough to be useful. In other words, they are synthetic chemicals, but the information used to make them is taken from living organisms.

Green chemistry

Two major goals of "green chemistry" are to develop chemicals that are less toxic or to make them in less toxic ways, preferably both. The development of pheromones and growth regulators are examples of green chemistry. These are toxic only to the insect whose lives they disrupt. Other examples can fulfill the green chemistry criteria too: ■ A herbicide (applied at only teaspoons per acre) affects only a plant enzyme, and has very low toxicity to humans and animals. ■ An insecticide (also only applied in tiny quantities) affects an insect enzyme, and shows low toxicity to non-target species. ■ One herbicide approved by the EPA for use on corn and soybeans has an LD_{50} in rats of greater than 500 mg/kg body weight; that is, it is only slightly toxic (Table 3.4). Moreover, the herbicide is not a teratogen or carcinogen, breaks down quickly in the environment, and does not threaten groundwater.

Table 16.2 Desirable characteristics in a pesticide

- Only a small amount is needed to kill targeted pests
- Low toxicity to non-target species
- Specific to one or a few pests
- A lifetime just long enough to kill target pests (i.e., does not persist)
- Degrades into benign products
- Does not bioaccumulate
- Does not runoff with water from application site
- Pests are slow to develop resistance to it

Note. Ideally a pesticide would have all these characteristics. In practice, certain characteristics are incompatible. For example, it is desirable that a pesticide not migrate from its application site. However, the reason it may not migrate is that it binds tightly to the soil and is not soluble in water – characteristics associated with the undesirable traits of environmental persistence and bioaccumulation.

The greenest alternative?

US Department of Agriculture scientists recently developed a crop protectant (not a pesticide). If it lives up to its potential, it could halve the use of pesticides. It is a simple product – processed kaolin (clay), not a synthetic chemical. This product, called *Surround*, when sprayed onto plants forms a film barrier that inhibits many species of insects and mites from feeding on them. It also reduces sun damage and heat stress. Its method of application is still being adjusted so that it does not drive beneficial insects away. This type of product has little toxicity – in fact, in some locales in the world people for unknown reasons eat clay. Because of its low toxicity, Surround didn't need to go through the usual EPA registration process, and is being test marketed. Again – recall the tenet of IPM – Surround does not eliminate pests, but manages them.

There is no "magic bullet" for successful agricultural pesticides, no totally safe green-chemistry pesticides, and no totally effective crop protectants. Ongoing research and development are needed to obtain many more green chemicals and crop protectants. And when you think of gardening, think of alternatives: http://audubononline.org/bird/at_home/alternatives.html.

SECTION V

Pesticide use in impoverished countries

Ignorant use of pesticides

Pesticide users in impoverished and developing countries often suffer much greater exposures than individuals in developed countries. The UN Food and Agriculture Organization estimates about 25 million people in developing countries are poisoned each year by improper use of dangerous pesticides, and about 220 000 die. (The WHO estimate is somewhat different: that, worldwide, 3 million people each year suffer acute pesticide poisoning and about 300 000 die. Either figure is tragic.) Large-plantation owners may not provide workers with personal protection or the education needed to use pesticides safely. Many small farmers are ignorant about the products they buy and how to use them safely. In one case of gross negligence, 24 children in a Peruvian village died after drinking milk into which a woman had mixed parathion to kill a stray dog. Salesmen are too often willing to sell banned pesticides made by unscrupulous manufacturers. Even carefully prepared labels are useless for farmers who cannot read. Many millions of children work or live in agricultural settings in Africa, Asia, and Latin America, and are often exposed to pesticides. Recall the Yaqui Indian children (Box 3.5). In one Cambodian village, one-quarter of the children (aged 6 to 12 years) who labored in agricultural fields or just lived and played nearby, suffered skin lesions attributed to pesticide exposure. Pesticide contamination of groundwater is obvious in some locales, much higher than in developed countries.

In China, many farmers, hoping to increase crop yields use great amounts of pesticides and synthetic fertilizer. Farmers in Guangdong province reportedly apply five times the world average of certain pesticides. Although DDT has been banned by worldwide treaty, except for use against malaria, China has applied for an exception to use it on crops. Farmers prefer the cheaper DDT although alternatives are available. However, they are now receiving bad publicity due to their practices, their fruit exports are low, and the Chinese who can afford it are buying foreign fruits; they express fear of local contamination as the reason for doing so.

Dangerous pesticides

Pesticides banned in many industrialized countries, such as methyl parathion, are still used in impoverished locales. In late 2002, the United Nations reported that the use of especially poisonous organophosphates continues to grow. Recall from Chapter 12 the *Basel Convention* on controlling imports of hazardous waste into developing countries. The Rotterdam Convention on Pesticides and Hazardous Chemicals serves a similar role to control imports of dangerous pesticides and other chemicals. A country receives information on chemicals it is considering importing, and can exclude those it cannot manage. However, if it gives its *prior informed consent* and imports a pesticide, the Convention assures good labeling standards and provides technical support. It ensures too that exporters comply with requirements. However, in late 2002, only 32 pesticide and other chemical products were controlled in this way. Another program (not a treaty), an International Code of Conduct on the Distribution and Use of Pesticides is administered under the auspices of the UN Food and

Agriculture Organization (FAO). Its aim is to reduce the widespread pesticide threats in the developing world.

Obsolete pesticides

The UN FAO estimates that 500 000 tonnes of unused–outdated pesticides still exist in developing countries, including old organochlorine pesticides such as DDT and dangerous organophosphates such as parathion and monocrotophos. These threaten human health and environments. The cost of destroying them is very high. Africa has no hazardous-waste destruction facilities, so old pesticides must be shipped elsewhere. There is an international campaign, albeit an inadequate one, to help. Japan, for example, is funding part of the cost of cleaning up pesticides in Mozambique, and intends to help other nations as well. The FAO has asked manufacturers to take back their outdated products, but the Global Crop Protection Federation, representing manufacturers, has been slow to help.

Moving away from pesticide use

Many conclude that safe pesticide use in impoverished locales is difficult or impossible. Thus, the UN FAO supports IPM and organic farming to minimize pesticide use. ■ In 1986, Indonesia's President Suharto banned the use of 57 pesticides used on rice. One reason was that growth of the brown plant hopper (BPH), one of the worst enemies of the rice crop, was actually enhanced by pesticide use, and rice yields using pesticides were lower than yields from rice fields managed by IPM. This happened because heavy pesticide applications killed off many of the natural predators of the BPH – such as dragon-flies, wasps, and spiders. Many amphibians and other non-target species were killed too. Since then, with assistance from the Indonesian government, the FAO has trained about a million farmers in the use of IPM. Training includes rice ecology, how pesticides affect ecosystems, how to recognize pests, and when they reach significant levels. The FAO now has training projects in more than 40 countries for a variety of crops. Pesticide use is absolutely minimized. An FAO Coordinator noted that, "countries across the Asia region are now at a crossroads where they must choose between a future of farmer-based, sustainable agriculture, or a return to the input-led systems fostered by the Green Revolution in decades past." ■ In Latin America, the Inter-American Development Bank loaned the Nicaraguan government money to help 14 000 farmers use IPM, while also practicing soil-conservation techniques including contour plowing, ditching, and terracing.

Many farmers are losing knowledge of farming techniques indigenous to their cultures. As UN Environment Program Director Klaus Töpfer states, "Enshrined in their cultures and customs are secrets of how to manage habitats and the land in environmentally friendly, sustainable ways." ■ In one case, farmers in South America's Andes, using a technique estimated to be 3000 years old, obtained much higher potatoe yields than farmers in other areas. ■ The African country of Ethiopia, after years of drought and soil degradation, is suffering famine and malnutrition. Government agents encouraged farmers to use synthetic pesticides and fertilizers to improve crop yields. But farmers had difficulty with, and often misused, pesticides. Human and animal poisonings resulted. The organization Save the Children recently began training Ethiopian farmers on how to use traditional methods and IPM. Farmers learned to recognize pests and beneficial insects, and how to enhance the populations of beneficial creatures. They did not automatically use synthetic pesticides. Instead when possible, they used local alternatives to pesticides including fermented cow's urine, and various plant extracts. Farmers using these methods improved crop yields, reduced pesticide use, and increased their incomes.

The United Nations is encouraging small farmers to take up organic farming. However, some agricultural scientists don't believe that organic agriculture can produce yields as high as pesticide-assisted agriculture. They point out that although organic farming may take less fossil-fuel energy, it takes more human labor. However, labor is plentiful in many poor countries, as is the desire to own and care for their land. An important benefit for farmers using IPM or organic farming is that they begin to trust in their own judgment, rather than automatically depending on pesticides.

SECTION VI

Using biological organisms

Not all pesticides are chemicals. There are *biological* pesticides, *botanical* pesticides, and *bioengineered organisms* (Table 16.3). Pyrethrum, purified from chrysanthemums, is an example of a botanical pesticide. Natural pyrethrums have limited uses, and more effective synthetic pyrethrins have been developed. Four insecticides available in the United States are derived from the neem tree, grown in India. These too have limited uses because, when exposed to sunlight, they quickly degrade to products that cannot kill pests. It may be possible to overcome some of their limitations.

A microbial pesticide is an actual microorganism, one that has pesticidal properties. It is applied as if it were a chemical pesticide. The best known microbial is the bacterium *Bacillus thuringiensis* (Bt) used to control caterpillars, beetles, and flies. Microbial insecticides such as Bt and baculoviruses are more selective than many chemical pesticides, thus lessening the threat to non-target species. However, like other pesticides, a microbial must be shown not to threaten humans, animals, or the environment. Also, although pesticides specific to one pest are environmentally desirable, they may be less profitable to the company that manufactures them because of this limited application.

Table 16.3 Alternatives to synthetic pesticides

Alternative	Definition	Examples
Natural	An extract prepared from living organism	An extract of chrysanthemum, tobacco, or the neem tree
Botanical	An ingredient purified from a natural extract	Pyrethrum purified from chrysanthemum extract or nicotine from tobacco extract
Biological[a]	A living agent that acts as a pesticide (e.g., a bacterium, insect, or fish)	An explosion in the rabbit population in Australia was controlled after release of a microbe that infected and killed them
Microbial[a]	A biological agent that is a microorganism (bacterium, virus, fungus, or protozoan)	The Bt virus or baculovirus, either of which can act as a pesticide
Bioengineered organism[b]	A living organism with genes – taken from another organism – inserted into its DNA. The genes allow it to make a substance (in this case, a pesticide) that it previously could not	• A plant with the Bt gene inserted into its DNA allowing it to produce a pesticide that repels insects • A plant given genes to produce a product that makes it resistant to herbicides

[a] These are not extracts or chemicals, but living organisms.

[b] In a *bioengineered organism*, a living organism produces a pesticide or other protective chemical after being given the necessary genetic material to do so.

Bioengineered organisms

A genetically engineered organism (GEO) – also known as a genetically modified (GM) organism – has foreign DNA inserted into its own genetic material. This gives the GEO the ability to make a new chemical, such as a pesticide, that it could not previously produce.[8] Why develop GEOs? Goals include increasing crop yield or crop nutritional value, reducing the need for pesticides, or providing disease resistance. A long-term goal is to develop GEOs with abilities such as being able to grow in salty or dry soils. A number of GM crops are already widely planted in the United States (Table 16.4)

Herbicide-resistant crops

Among the major GM crops grown in the United States are herbicide-resistant soybean, canola, and corn (Table 16.4). Prior to their development, the only time farmers could use herbicides on crops such as corn or soybeans was before the plants emerged from the ground – otherwise the herbicide killed the crop too. Farmers can now spray herbicides as the crop grows, e.g., to kill milkweed plants growing among corn plants. This leads to the accusation that these GEOs promote, not discourage pesticide use. Manufacturers respond that herbicide-resistant crops, because the herbicide is applied when most effective, actually lessen the need for spraying. Currently, it is still unclear as to whether herbicide use has increased or decreased.

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[8] GEOs are also called transgenic organisms or genetically modified (GM) organisms.

Table 16.4 Transgenic crops planted in the largest acreage

- Herbicide-tolerant soybean
- Herbicide-tolerant canola
- Herbicide-tolerant corn
- Bt corn (gene from *B. thuringiensis*) conferring insect resistance
- Cotton (insect-resistant/herbicide-tolerant)

In 1999, the United States planted 72 million acres (29 million hectares) of genetically modified (GM) crops. Other GM species have been or are being developed, including cotton, but these are still grown on smaller acreages.
Table adapted from Hileman, B. At last: a biosafety pact.
Chemical and Engineering News, **78**(7), 14 February, 2000, 65–74.

And there are yet other concerns. If herbicide use increases, this would enhance the development of weeds that are resistant to herbicides, so more herbicide would be needed to control resistant weeds. ■ But herbicide-resistant crops may have an environmental advantage – farmers can grow them using no-till and conservation-tillage techniques. This greatly lowers soil erosion and pesticide runoff, and also retains water in the soil and increases its organic matter. However, the extent to which soil conservation is actually increasing has not yet been studied.[9]

Insect-resistant crops

Other major GM crops are corn and cotton into which genes from the microbe *Bacillus thuringiensis* (Bt) have been incorporated. This gives a crop that produces its own insecticide, a *biopesticide* (in this case a Bt insecticide). There are a number of different Bt genes coding for different insecticides. So, producers claim that when resistance develops to one biopesticide, a different gene can be substituted. It is not yet clear whether less insecticide is used on these crops.[10] In 1999, a US Department of Agriculture study found that insect-resistant cotton and corn produced statistically higher yields although results much varied depending on the region, how severe pest infestations were, etc.

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[9] Although not often in the public eye, soil-erosion problems are unrelenting. In the United States only about one-eighth of farmland is flat enough to prevent erosion. Estimates are that up to half of US topsoil has run off into rivers and seas since white settlers began to farm. We are "mining" the soil (and often the groundwater beneath it). One corrective measure is *no-till* farming. This involves no plowing and almost no runoff, but herbicides must be used to kill the cover crop on the soil. *Conservation tillage* disks the former crop residue into the top few inches of soil; this also greatly minimizes soil erosion and runoff of pesticides and fertilizer. Growing perennial crops is another way to prevent erosion and runoff. Developing perennial grains such as wheat, corn and rice could be immensely helpful.

[10] Organic farmers oppose incorporating the Bt or other biopesticidal genes into crops. They use the microbial pesticide *Bacillus thuringiensis* in organic farming, but do so judiciously to delay the development of insect resistance. The problem with incorporating such genes into crop DNA is that once the Bt genes are there, they are always "on," always producing insecticide. This may hasten the development of resistance. The EPA requires a pest-resistance management plan when such a crop is registered to prevent, or at least postpone, the development of insect resistance. The EPA also limits planting of Bt crops in certain regions.

Enhancing GEO benefits

Table 16.5 summarizes potential benefits and risks of GEOs. Two US government scientists, L. L. Wolfenbarger and P. R. Phifer,[11] believe we can prolong possible benefits associated with genetically engineered plants while also minimizing possible ecological risks in two ways. (1) Take measures to slow the development of resistance (to the products of the transplanted genes). (2) Take measures to prevent transfer of genes from GEOs to the wild, genes that may have a negative impact on wild populations.

A biosafety protocol

In 2000, the Cartagena Protocol on Biosafety was adopted to regulate international trade in GEOs. The goal of this treaty is to protect the environment from risks posed by transgenic seed, plants (including agricultural commodities), fish, live animals, and microbes. One requirement is that shipments containing transgenic crops be labeled on the manifest with "may contain living modified organisms." Although some environmentalists and to a lesser extent industry were pleased with the protocol, tremendous controversies remain. Citizens of EU countries are particularly anti-GEO. If controversies remain unresolved, they will surely affect the long-term success of transgenic crops.[12]

Box 16.4 GEOs in developing countries

A Kenyan woman studying biotechnology in the United States said that rural women in her country spend 60% of a working day pulling weeds. Her mother spent a lifetime weeding; so had she until she was 15 years old. She said, a "woman's place is in a lab engineering herbicide-resistant crops so that other women don't have to pull weeds." Seven national science academies – including those of the United States, the United Kingdom, Brazil, China, India and Mexico – promote biotechnology as a means to lessen hunger and poverty. They advocate research and development efforts directed specifically to the special needs of developing countries. Some scientists in developing countries strongly support transgenic crops saying that the impoverished world doesn't have the luxury of "lengthy disputes about real or imagined risks (and must focus on) a rigorous risk–benefit analysis." Many groups, some scientists, and some governments in impoverished countries have strong anti-GEO sentiments. In one instance, an African country in 2002, although suffering from a famine refused to accept transgenic grain shipments.

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[11] Wolfenbarger, L. L. and Phifer, P. R. The ecological risks and benefits of genetically engineered plants. *Science*, **290**(5499), 15 December, 2000, 2088–93.

[12] For a flavor of these issues read (see Further reading): B. Hileman, At last: a biosafety pact; and Dan Ferber, Food fright: risks and benefits: GM crops in the cross hairs. Hileman, in another article (Polarization over biotech food) suggests that we could help clarify some issues if we don't ask overarching questions such as: Are all transgenic crops safe or risky? Instead ask: Would this particular crop or animal help farmers, health, the environment, and economy in a particular region. Ask too: Is there a better way to reach these goals? Compare the GM crop to the crop grown conventionally as well as under alternative systems. If the transgenic crop is clearly superior on these broad grounds, it may have a chance to gain acceptance.

Table 16.5 Potential benefits and risks of genetically engineered organisms

	Explanation or example
Potential benefits	
1. Increase crop yield	1. Corn protected from pests has increased yield
2. Increase nutrients	2. A genetically modified rice that produces its own vitamin A
3. Reduce need for pesticide	3. A crop producing its own Bt toxin may need less insecticide
4. Soil conservation	4. Herbicide-resistant soybean grows although weeds were not tilled into soil – so less soil erosion
5. Preserve wildlife habitat	5. If there is greater crop productivity, less land may be farmed
6. Other benefits	6. Crops may be developed that, e.g., grow in salty or dry soil
7. Phytoremediation of contaminated soil	7. Use genetically modified plants to take up pollutants from soil or water
Potential risks	
1. Development of pesticide resistance	1. Insects initially killed by Bt toxin in corn develop resistance to it. Growers spray more not less pesticides[a]
2. Gene flow (invasiveness)	2. Genes "flow" into ecosystem (hybridize with weedy relatives and transfer resistance to them) with adverse effects on agriculture[b]
3. Harms non-target species	3. Corn producing Bt insecticide kills not only target species, but also, e.g., kills larvae of monarch butterfly;[c] or, protein produced by new gene may be a human allergen[d]
4. Indirect harm to ecosystem	4. If you reduce the population of a weed that provided seeds eaten by other insects or birds, they have less food
5. Antibiotic resistance	5. Antibiotic-resistance genes transferred to pathogens in body[e]

[a] When Bt bacteria are used as a pesticide they are sprayed once or twice a season. But, inserted into a plant genome, Bt genes are always "on," that is, they are always producing the Bt insecticide increasing the risk of rapid development of insect resistance to it.

[b] Most scientists say that genes could not persist in the wild unless they have a selective advantage. But others believe that, as GEOs are more-widely planted, the chances of this happening will increase.

[c] There is general, not universal, agreement that monarch larvae are not adversely affected. Yet it wouldn't be surprising if they were because when Bt bacterial sprays are used they do affect some butterflies and moths (Table 16.3).

[d] However, producers routinely screen GEOs for their potential to be allergens. (Classical plant-breeding techniques can also introduce potential allergens.)

[e] Why are antibiotic-resistance genes in the GEO? Plant geneticists attach genes that they want to introduce into plants to an antibiotic-resistance gene. This allows them to separate out plants with the desired genes: an antibiotic kills the non-resistant plants, leaving alive the plants with the incorporated genes. Some fear the antibiotic-resistance gene could be transferred to pathogens in the body making them antibiotic resistant too. Several scientific panels evaluated this concern: "Unanimously, the verdict has been that the chance of antibiotic-resistance genes getting into intestinal bacteria is minuscule." And if they did get in, "the virtually unanimous verdict is that it wouldn't matter" because the same resistance genes are already present in many of the bugs.

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Chapter 17

Pollution at home

> "Seeing things differently is the first step toward doing things differently."
>
> *Anon.*

Twenty-five years ago, the US EPA, working with Harvard University, was studying the sources of various environmental pollutants. They made what was to them a startling observation: regardless of which community they studied – its location; whether rural or urban; lightly or highly industrialized; and regardless of sex, age, smoking habits, and occupation – indoor air pollution was the major source of exposure to many air pollutants. This is perhaps not surprising: most people spend 90% or more of their time indoors, indoor sources emit many of the same pollutants as outdoors sources, and mixing with outdoor air may be slow to occur. In the following years, the Advisory Board of the US EPA ranked indoor air pollution as a priority environmental health risk. **Section I** of this chapter reviews specific contaminants that affect indoor air quality: combustion pollutants (including tobacco smoke), volatile organic chemicals (VOCs), radon, and biological pollutants. It briefly overviews too the major impact that combustion particulates have on people in impoverished homes of less-developed countries. **Section II** delves into hazardous household products and household hazardous waste, and describes two old hazards that remain with us, asbestos and lead paint.

SECTION I

Indoor air pollution

Contaminants affecting indoor air quality spring from many sources (Table 17.1).

- Particulates and several criteria air pollutants (Chapter 5) are emitted by combustion appliances including wood stoves, fireplaces, gas stoves, and kerosene heaters.

Table 17.1 Indoor air pollutants

Sources	Pollutants released
Household products	
• Paints, stains, thinners, strippers, polishes, cleansers, solvents, air fresheners • Cosmetics, perfumes, and colognes • Hobby supplies (paints, glues, metals, wood, glass, others) • Propellants in aerosol sprays • Pesticides and their solvents	These various products can emit VOCs such as formaldehyde, benzene, toluene, xylene, and hexane. Many other VOCs are also possible, depending on the products used. Some also emit particulates and other pollutants.
Household furnishings	
• Drapes, upholstered furniture, pressed-wood in cabinets, walls, sub-flooring	New furnishings. Formaldehyde and other VOCs
• Carpets, shelving, other surfaces, "dust catchers" (also, see biological hazards)	Older furnishings. Dust, biological pollutants
• Carpets, furnishings, bedding	Dust mites and dust
Dust and dirt getting into the home	These can contain pesticide residues, metals, and biological pollutants
Combustion sources	
• Oil or gas furnace, unvented kerosene or gas stoves, wood stoves, fireplaces • Gas water heater or clothing dryer • Environmental tobacco smoke (ETS)	Without good controls, combustion appliances release carbon monoxide, nitrogen oxides, sulfur dioxide, particulates (sometimes formaldehyde, benzene, and other VOCs). ETS emits these and many others too.
Biological hazards	
• Moist areas (basement, bathroom, etc.)	Mold VOCs, bacteria, bacterial toxins, viruses
• Humidifiers and dehumidifiers	If not kept clean, these can emit all of the above
• Pets, intruding rodents and insects	Animal dander, dried saliva, urine
• Outdoor air	Pollen and dust
Hazards old and new	
• Old paint	Lead
• Old insulation(furnace pipes, old tiles)	Asbestos
• Construction materials, wood paneling	VOCs including formaldehyde
• New carpets, padding, adhesives	VOCs
• Painting, stripping old paint, etc.	VOCs
Basement floor (cracks, sump openings)	Radon
Household water	
• Municipal chlorinated drinking water	Radon
• Well water	Chloroform and other VOCs
	Radon, sometimes VOCs

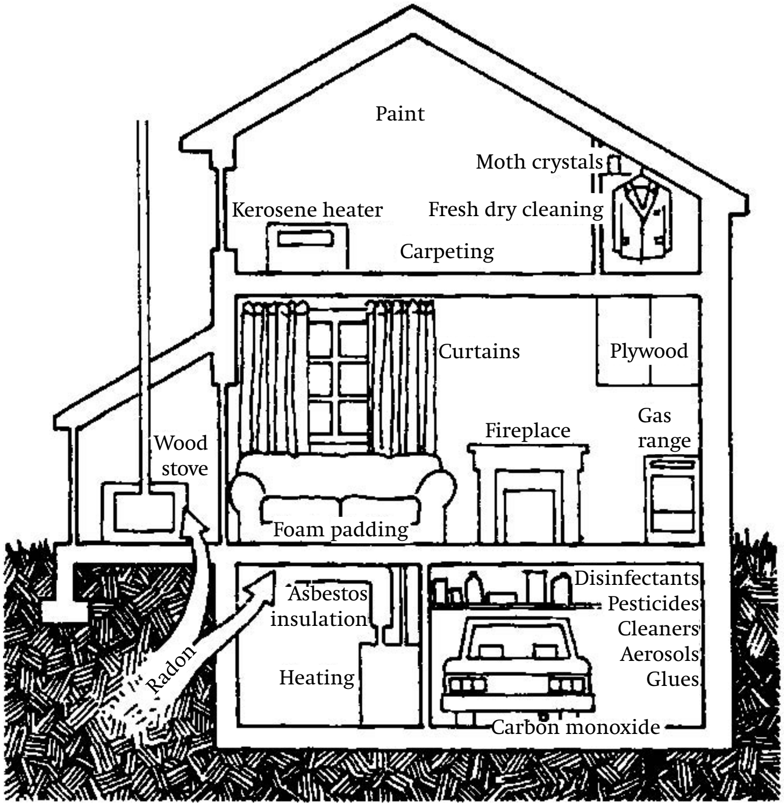

Figure 17.1 Sources of indoor air pollutants

- VOCs are emitted from construction materials (such as particle board) and many consumer products including cleansers, polishes, paints, moth balls, glue, rugs, furniture, drapes, clothing, and hobby materials. Chlorinated water emits VOCs too.
- Biological contaminants grow in moist areas in homes, and become airborne.
- The radioactive gas radon seeps up from rocks and soil under homes into indoor air, and also enters air from well water pumped into the home (Table 17.1 and Figure 17.1).
- Older homes may have special problems such as flaking lead paint or asbestos. Some too may have accumulated more biological contaminants from persistent wet places or old rugs.

Effects of indoor air pollutants

Health effects may be negligible or major depending on the pollutant, its concentration, how one is exposed and the length of exposure. Acute effects can result from high levels of a pollutant. Chronic effects can result from lower ongoing exposure. Examples: ■ Irritation of eyes, nose, and throat can result from exposure to nitrogen oxides or formaldehyde. ■ Allergies or infections can result from exposure to airborne microorganisms. ■ Flu-like symptoms or headaches can result from low levels of carbon monoxide (CO) emitted by combustion appliances. High CO levels can be deadly.

Illustrations of adverse effects resulting from household exposures follow.

- A woman was temporarily paralyzed after vigorously applying flea spray inside her home without adequate ventilation.
- A university student fainted while using a spray cleaner on her bathtub in a small, unventilated bathroom.
- A student reported coughing and choking after using an aerosol spray near his face.
- Some people report sneezing and tearing up just by walking through a store aisle lined with VOC-emitting products.
- Chronic effects, sometimes life threatening, also occur. ■ A woman, whose hobby was refinishing furniture, developed liver cirrhosis after using paint stripper in a closed room over several winter months. ■ A man stripped lead paint from the interior of his old house without any protection. After 4 months of this activity, he developed an ongoing fever and other symptoms. He was found to have a blood lead level of 116 μg/100 ml, the highest ever seen in the state of Maine.

Many reactions are not serious and are quickly over. Or, as in the case of the persons overexposed to flea killer, paint stripper, and leaded paint, reactions can be severe. The lives of other people are made miserable by a syndrome called "multiple chemical sensitivity." These individuals are hypersensitive to the odors of VOCs. Others are made equally miserable from the emissions of molds growing in the home.

Reducing indoor air pollution

Precautionary steps to protect one's home against harmful emissions follow.

- Become aware of products emitting VOCs or other pollutants. Unless their use is necessary, consider eliminating them; that is, practice source reduction (pollution prevention, P^2).
- An important, even vital P^2 step is to assure that your home does not develop long-lasting wet spots. These promote the growth of molds, which release VOCs and spores that promote and aggravate allergies. Occasionally, reactions to mold toxins are deadly. Mold often grows in moist basements, but no place in the home is immune. In bathrooms and other places that are often moist, make sure that fans are installed and vent them to the outside.
- Because you cannot eliminate every source likely to affect indoor air quality, be careful that your home has good ventilation. Make sure your stove has an exhaust fan vented to the outside. Especially in a modern airtight home, installing an air-to-air heat exchanger can provide good ventilation with minimum heat loss. One person phrased the need for both energy conservation and good ventilation by saying, "Seal tight, ventilate right." Electronic air cleaners and

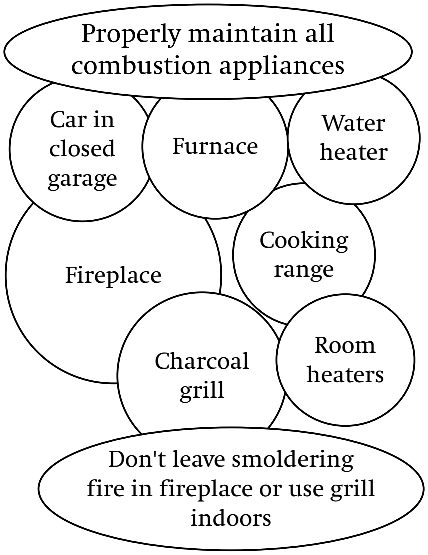

Figure 17.2 Sources of carbon monoxide and preventing possible carbon monoxide problems

high-efficiency particulate air (HEPA) filters can filter air by trapping dust, fibers, pollens, skin flakes, and pet dander. However, filters do not trap VOCs, and they need to be regularly changed.

Combustion pollutants

Almost all homes use combustion appliances such as furnaces, stoves, fireplaces, gas-burning appliances, or kerosene heaters. Many homes have smokers too. In impoverished countries, cooking and heating fires may be built inside the home, often with little ventilation.

Combustion pollutants and sources

- Carbon monoxide. In enclosed spaces CO causes hundreds of deaths in the United States each year. Lower levels of this colorless, odorless gas can lead to headaches, dizziness, nausea, and flu-like symptoms. The US Consumer Product Safety Commission recommends that households install CO detectors that will sound an alarm if CO reaches unsafe levels. To largely eliminate CO emissions, combustion appliances need careful maintenance. This is true of wood, gas, or coal stoves; furnaces of all types; fireplaces; and chimneys and their connections. Kerosene heaters can be major CO sources, and should be vented outdoors. Other precautions include venting stove hoods to the outside and installing appliances according to the manufacturer's instructions. Don't leave a fire smoldering in a fireplace; if a fire is still burning, close it off from the room (Figure 17.2).
- Nitrogen oxides. Efficient burning is typically desirable except that a very hot flame promotes reactions between atmospheric nitrogen and oxygen to produce nitrogen oxides. These can irritate eyes, nose, and throat, increase asthma attacks and susceptibility to infection.

Nitrogen oxides may be found at significant levels in homes with a gas stove or dryer, or a kerosene heater.

- Particulates. Wood-burning stoves and fireplaces are a major source of particulates in indoor air. This is true anywhere. It is much more true in the homes of hundreds of millions of the world's impoverished people burning biomass such as wood. There concentrations are often so high that millions of deaths a year are attributed to them.

Other sources of combustion pollutants

- Environmental tobacco smoke (ETS). When present, ETS poses serious environmental health risks. Burning tobacco emits particulates and hundreds of chemicals, including carbon monoxide, benzene, formaldehyde, cadmium, lead, arsenic, even tiny amounts of dioxins. Especially in enclosed surroundings, levels of combustion products build up. Children living in homes with smokers often develop respiratory problems or such problems may worsen. Smokers also run the risk of lung cancer, and severe pulmonary and heart disease. The association of ETS with heart diseases results from the CO in smoke. Inhaled CO deprives the body, the heart included, of oxygen. A cigarette left smoldering produces more CO than one actively smoked.
- Wood-burning stoves and fireplaces. The fires may be lovely, but effects on indoor air quality are less benign. They emit VOCs, CO, nitrogen oxides, and can be large sources of particulates and the substances adsorbed onto them including polycyclic aromatic hydrocarbons (PAHs). Many are very-fine particulates, breathed deeply into the lungs. Particulates contribute to or cause respiratory diseases, and sometimes, infections. They can also irritate the eyes, nose, and throat. Very-efficient, but costly, stoves and fireplaces exist that greatly reduce stove and fireplace emissions.
- Garages. Homes with garages attached to or under them, expose occupants to combustion products from the exhausts of automobiles, lawnmowers, and other internal combustion engines. In addition to CO, much of the benzene in indoor air has been traced to attached garages. Car exhaust, stoves and furnaces also emit formaldehyde.

Volatile organic chemicals

VOC sources are almost ubiquitous

■ Many building materials, furnishings, and often new clothing emit VOCs. ■ Paints, stains, paint thinners and strippers, varnishes, and turpentine emit VOCs too. When paint is in use, it is the number one contributor to VOCs in indoor air. This was a greater problem when oil-based paints were often used indoors, but water-based paints are now more commonly used. ■ Pesticides, if not volatile themselves, can volatilize when discharged in aerosol sprays. ■ Floor and furniture polishes and some waxes emit VOCs, as do cleaners used in bathrooms and kitchens. ■ So do many personal-care products such as nail polish, nail-polish removers, and hair sprays. ■ Motor-vehicle products such as gasoline and oils emit VOCs. ■ Art and craft materials, glues, paints, etc. emit VOCs. Hobbies that generate pollutants, sometimes in significant amounts include model building, photography, ceramics, painting, jewelry making, metal- and stained-glass working, and pottery making. Some of these activities generate metal fumes too. Woodworking generates significant amounts of VOCs and particulates, so much so that some individuals are forced to give up this activity (see Box 17.1). ■ Aerosol spray cans emit VOCs and tiny particulates. Hand-pump sprays are a lesser problem.

Advice

Don't try to remember every product that emits VOCs. Instead, remember that almost any consumer product *can* pose a risk. Routinely, read labels and follow instructions. If "danger" or "poison" is on the label, consider an alternative.

Box 17.1 Some pollutants are difficult to avoid

We can avoid many VOCs and hazardous chemicals by shunning products that contain them, but some are too prevalent to avoid totally. As you read about the chemicals below, recall that "the dose makes the poison," and that exposures are often low. However, if a product is thoughtlessly used, air concentrations can rapidly increase, as happened with the girl who vigorously sprayed a cleanser into the air of a tiny closed bathroom. In addition, some people are exceptionally sensitive. A third consideration is that we are typically exposed to mixtures of chemicals, not just one. This makes it much harder to assess the impact.

Polycyclic aromatic hydrocarbons (PAHs) are a family of more than a hundred chemicals. They do occur naturally in petroleum but our major exposure to PAHs is from combustion, they are products of incomplete combustion. Soot from wood stoves and fireplaces contains PAHs; kerosene stoves can be sources too; smokers in the home can produce large amounts. The PAH benzo[*a*]pyrene (BaP) is an especially potent carcinogen; others are mutagens. Because combustion is so prevalent, we cannot totally avoid these contaminants of our air, food, and water. Even browned foods and toast contain tiny quantities, and char-grilled foods have larger amounts. PAHs are common contaminants in carpets. Two US EPA researchers pointed out that some urban infants are exposed to levels of BaP equivalent to smoking three cigarettes a day.

Formaldehyde (HCHO) has the ability to react with other chemicals, linking them into useful polymers. It is an exceptionally useful chemical used in and emitted by dozens of products including construction materials; resins and glues in pressed-wood products (particleboard, fiberboard, and hardwood plywood); and sealants in floors and cabinets and other furniture. Drapes, wall coverings, and permanent-press clothing contain and emit formaldehyde. Many cosmetics also emit tiny amounts although they can dissipate quickly with good ventilation. HCHO functions as a fungicide in latex paints and wallpaper. Unfortunately, the same property that makes formaldehyde useful as an industrial chemical allows it to irritate the moist membranes in our respiratory tract and eyes. Some individuals react severely.

Fatigue and nausea are among possible symptoms. Others develop an allergy and become sensitive to even tiny amounts of formaldehyde.[1] For especially sensitive individuals, formaldehyde home monitors are available.

When formaldehyde reacts to form polymers it becomes an integral part of the product. The problem arises from unreacted formaldehyde, which escapes into the air. Some products, e.g., plywood, particleboard (found in cabinets and other furniture), and sub-flooring, can continue emitting for months after installation, or for weeks for plastic-laminate counters. However, formaldehyde emissions from many building products have been reduced in recent years. ■ Ask for low-formaldehyde emitters when you buy these products. New carpets are no longer a HCHO source. When possible, do remodeling and install new furnishings in the summer when windows can be open. Wash wrinkle-resistant clothing before wearing them. Clean permanent-press drapes before installation or at least install them with plenty of ventilation. (A new method to make wrinkle-free fabrics without formaldehyde was recently reported. This is an example of "green chemistry," of design for the environment.)

Benzene occurs naturally in petroleum. Vapor traps protect us from VOCs including benzene as we pump gasoline, but benzene is in motor-vehicle exhausts too. Benzene was added to gasoline as an anti-knock agent years ago to replace the metal lead. However, benzene can be toxic too and the amount in gasoline has been lowered. At levels once found in occupational settings, benzene was associated with leukemia and aplastic anemia. Smokers are exposed to benzene too, but at considerably lower levels than were industrial workers. Non-smokers are exposed to lower levels still. Nonetheless, benzene in indoor air may be three times higher than outdoor air. It is found in small amounts in the fumes evaporating from glues, paints, furniture wax, detergents, nail polish and polish remover. Wood-burning stoves and fireplaces can be sources. Garages attached to homes allow gasoline fumes to seep inside. Stored paints that are incompletely sealed and stored products containing gasoline are sources too. Although benzene levels in homes are typically small, regulatory agencies treat exposure to a cancer-causing substance at any level greater than zero as posing some risk. However, tiny amounts of benzene are naturally present in water and in foods such as nuts, fruit, vegetables, and dairy products.

Tetrachloroethylene (perchloroethylene or PERC) is another small, but ongoing exposure for most wearing dry-cleaned clothing. At high doses it is a carcinogen in experimental animals. Dry-cleaners have the highest exposures. People living in buildings with dry-cleaning facilities can have quite high exposures too. Wearing dry-cleaned clothing or entering closets containing dry-cleaned clothing involves some exposure. Compared with earlier years, less PERC remains in dry-cleaned clothing. We can reduce it further by airing dry-cleaned clothing before wearing it. The US EPA is working with industry to develop alternative cleaning methods, and PERC use is expected to be phased out.

Paradichlorobenzene is added to stored clothing and other fabrics to repel moths. It is also found in some toilet disinfectants, deodorizers, and air "fresheners."

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[1] We don't develop allergies to molecules as simple as formaldehyde, but formaldehyde reacts with proteins in the body. The formaldehyde-linked proteins can lead to allergic reactions. At high levels (not found in homes), it causes nasal cancer in rodents. Even the formaldehyde levels in our homes present a hypothetical risk of cancer.

Like the chemicals mentioned above it too is an animal carcinogen at high doses. Almost all exposure to paradichlorobenzene occurs indoors. Of 1000 Americans selected at random, more than 95% had detectable levels in their urine or blood. Depending on the brand of air freshener, other ingredients are present too such as camphor, alcohol, or the lemony-smelling limonene. As the University of California *Wellness Letter* – a health news letter – points out, a product label may say "natural, but natural doesn't necessarily mean you want it in your home." Disperse unwanted odors by increasing home ventilation, or sprinkling baking soda in areas needing odor control.

Other indoor pollutants. The chemicals discussed above are some of the well-studied indoor contaminants. Investigations on other chemicals are at earlier stages. *Phthalates*, a family of chemicals commonly used as plasticizers in plastic products are among other chemicals being more carefully examined as indoor air pollutants. Because phthalates are not chemically bound to the matrix of a product, they can leach out into air and house dust. They have been found in home air at levels as much as ten-fold higher than PAHs. House dust could be a large source of phthalate exposure for children. Finding detectable amounts of phthalates in indoor air does not necessarily indicate a problem. The concern is that we find so many substances in indoor air. This raises the topic of chemical mixtures.

Does the impact of a mixture differ from that of a lone chemical? Consider a study in which scientists studied people's reactions to VOCs in the air they were breathing. Researchers tested their reaction to a number of VOCs, at first doing so one chemical at a time. They looked at what concentration of each chemical could cause objectively measurable amounts of eye or nasal irritation. Subsequently, they tested the chemicals again, but in mixtures. With mixtures, irritations were more likely to occur. More investigations are needed because it is to mixtures that we are most often exposed. ■ At the same time, notice that the studied concentrations were high enough actually to cause irritation. In homes, contaminant concentrations are probably lower or much lower. Still, the conclusion holds that it is prudent to be aware of VOCs, don't use more than is necessary, and use them with care.

Effects of VOCs

Some of the many potential ill-effects of VOCs were described earlier in this chapter.

Recommendations for reducing VOC emissions

1. *Avoid buying products that are not needed.*
2. *Maintain good ventilation.*
3. *Read labels.* This is true not only of products such as pesticides, but also of cleaning products, polishes, and cosmetics.
4. *Use the minimum amount* of a VOC-emitting product that will do the job.
5. We can also ask for products with low emissions such as low-formaldehyde-emitting wood products. Increasingly, paints have lower VOCs. As a means of pressuring manufacturers to develop more such products, it is recommended that consumers continue to ask for them even if they are not now available.

The EPA cannot regulate VOC-emitting products, but actively studies them, and works with manufacturers to change product composition. However, some individuals point out that, quite aside from a low-VOC-emitting product, consumers want products that do just as good a job as high VOC emitters. This will take time.

Moisture

Chronic moisture is a major enemy of human health, and also of the structural integrity of the house itself. Health concerns arising from moisture result because wetness supports mold and bacteria growth. Molds emit the bioaerosols, spores (which are particulates), and also emit VOCs detected as a moldy smell. Some mold aerosols contain highly toxic *mycotoxins*. Mold emissions are at best a nuisance; at worst they cause or aggravate respiratory diseases and allergies, or result in infections.

Moisture sources and remediation

Home sources of moisture include humidifiers, air conditioners, ventilation systems, and refrigerator drip pans; others are damp attics and basements. When a cold wall exposed to moisture hits the dew point, moisture settles onto it, and the wall can become a place for mold growth. So can water-damaged areas and water-damaged carpets or furniture, papers, and books. ■ If a place is warm as well as moist, it is especially attractive to microorganism growth. ■ Plants in the home can be healthy, but, kept too moist, they too encourage microbial growth. Changing plant soils frequently can minimize mold growth. Mold infestations are often detected as a well-known "moldy" smell. If enough mold grows, it can be seen as well.[2]

A device sold at hardware stores can measure indoor humidity. Recommended humidity levels are 30% to 50% although some argue that anything over 30% encourages growth of undesired organisms. However, especially in summer, humidity may naturally be higher. ■ Recommended actions. When indoor air is too dry in the winter or in desert homes, health specialists may recommend drinking more water rather than installing a humidifier. If you use a humidifier, choose one generating steam, not cold mist. If using a cold-mist humidifier, fill it with deionized water to avoid the mineral particulates that tap water can generate. Regularly clean humidifiers and dehumidifiers to prevent microorganism growth. More generally, make sure that wet places do not persist anywhere in the home by properly maintaining air conditioners, ventilation systems, and refrigerator drip pans; change air-conditioner filters as recommended.

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[2] An estimated 25% of the world's biomass is in the fungal kingdom. This includes molds and other members of their family such as mildew. Outdoors, molds play the vital role of degrading organic matter. It is indoor growth which presents problems. Avoiding mold growth inside homes is worth the vigilance that is necessary.

Diluted bleach can be used to clean bathrooms contaminated with mold if necessary. However, damaged furnishings often cannot easily be cleaned, and may need to be discarded. ■ As with indoor VOCs, always maintain good ventilation. A particulate-trapping air purifier can remove mold spores.

Biological pollutants

The molds just described are biological contaminants and produce airborne contaminants such as spores. However, the word biological goes beyond microbes. Biological pollutants include pollens, animal dander, dust mites and their feces, cockroaches and their feces, cat saliva, rodent urine; that is, a great many biological substances can become contaminants of indoor air. Almost any of these can cause allergies. Airborne microbes can cause allergic reactions in sensitive individuals; bits of dead cockroaches or plants can also be allergenic. About 15% of people are allergic to dust-mite feces. Dust-mite and cockroach exposure is associated with an increased likelihood of asthma. Some microbes cause infectious diseases.

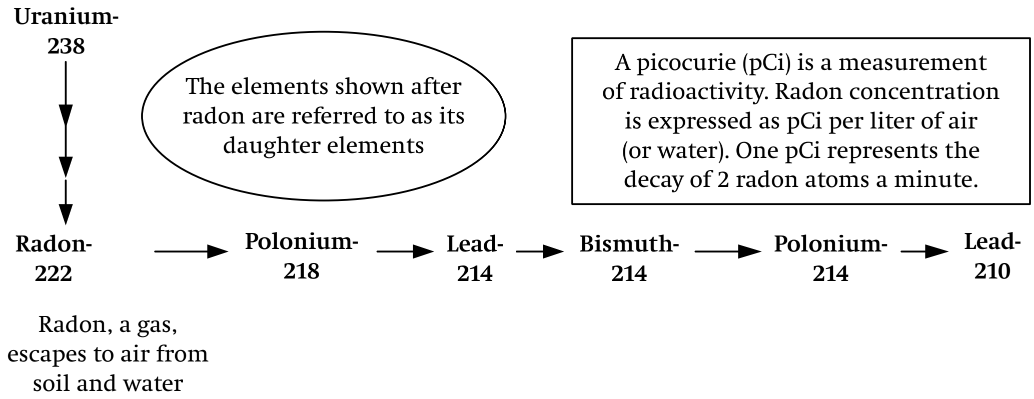
Sources and remediation

Sources of molds were discussed above. Other sources of biological contaminants are carpets, mattresses, and other bedding, which often have dust mites. Pollens are contaminants originating outdoors that enter the home with outside air or are carried in on pets. Animal dander and cat saliva obviously come from pets. Cockroaches often find their way inside especially in warm regions. There their body parts and feces can enter a home's dust. After it dries, cat saliva or rodent urine can also become airborne.

Depending upon the contaminants, many prevention and remediation strategies are possible. Maintain a home without the food particles that attract cockroaches. Seal cracks that allow cockroaches, ants, and other insects to enter. Maintain clean carpets. Consider wood flooring instead of carpeting, or use washable throw rugs. Allergic people must sometimes give pets away. There are ways to allergy-proof a home for especially sensitive individuals. Libraries and bookstores are sources of more information, as are physicians and the Internet, including sources at the end of this chapter.

Dust and dirt

A US EPA study provided the interesting information that – like the Peanuts cartoon character *Pig-Pen* – each of us moves about in a cloud of tiny particles. These are released from clothing, carpets, furniture, and other items, stirred up when we move around or when cooking. Dust particles (particulates) can hold almost any contaminant capable of becoming airborne – molds, bacteria, pesticide residues from



The elements shown after radon are referred to as its daughter elements

A picocurie (pCi) is a measurement of radioactivity. Radon concentration is expressed as pCi per liter of air (or water). One pCi represents the decay of 2 radon atoms a minute.

Radon, a gas, escapes to air from soil and water

Figure 17.3 Radon and its relatives

lawns, leaded dust, or anything tracked in with dirt on shoes. These contaminants are also deposited onto carpets and furniture. Carpets can be almost impossible to keep completely clean. Vacuuming carpets or sweeping wood floors gives rise to airborne dust. To lessen dust, damp-mop the floor before sweeping. Plants, artificial flowers, and dried arrangements are truly dust catchers. Get in the habit of leaving shoes in the entry way.

Radon

Radon (radon-222 or ^{222}Rn), is a natural radioactive gas commonly found in indoor air. Radon's ultimate source is *uranium* (uranium-238 or ^{238}U). In its turn, the radioactive element ^{238}U is naturally found in soil and rocks throughout the world. ^{238}U goes through a series of decay reactions to form ^{222}Rn (Figure 17.3). Because radon is a gas, it creeps to the surface as it is formed. If it surfaces outside, it dissipates into the atmosphere. However, if it surfaces beneath a house or other building, it can seep up through openings into indoor air. There, unless ventilation is very good, its concentration builds up especially on the floor where it surfaced. Radon in schools can be a concern. Trailers do not contact the Earth and so are spared radon. Radon levels in outdoor air range between 0.1and 0.4 pCi/l (pCi = picocurie, a unit of radioactivity). An average home has over 1 pCi/l in its air. In the United States, the *action level* for radon in indoor air is 4 pCi/l: if the radon level is 4 pCi/l or higher, the EPA recommends taking action to lower it.[3] An estimated 6 to 8 million American homes have levels greater than 4 pCi/l. Even 1 pCi/l is equivalent to undergoing about 50 chest X-rays a year. Canada has a higher action level for radon in homes, 20 pCi/l. Action levels for the United Kingdom and Germany are between 3 and 10 pCi/l. See Boxes 17.2 and 17.3.

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[3] This does not mean that radon levels below 4 pCi/l are safe. As is the case for carcinogenic chemicals, any exposure to ionizing radiation greater than zero is considered to pose some risk. Thus, even small amounts of radioactive radon, including that in outdoor air, are seen as posing some risk.

Why radon concerns us

As a radioisotope undergoes decay, it emits *ionizing radiation* – an alpha or a beta particle, or gamma rays. Any of these can ionize the atoms that are hit by stripping electrons from them. In living tissue, this may damage the genetic material, DNA. The *half-life* of a radioisotope indicates how long it takes for one-half of its atoms to undergo decay. Radon-222 has a half-life of 3.8 days, so the average radon atom breathed into the lungs is breathed out again before it decays. The major problem is not radon-222 itself, but its solid radioactive daughter elements. The first of these is *polonium-218*, which results from the decay of radon-222 ($^{222}Rn \rightarrow {}^{218}Po$ + alpha particle). Polonium-218 and *polonium-214* are solids, not gases, and can attach to dust particles in the air. Unlike inhaling a gas, if the dust is inhaled, solid elements can be deposited onto airway walls and reside long enough to decay. The solid daughters polonium-218 and polonium-214 have half-lives of 3 minutes and less than 1 second, respectively. They can decay in the lung, emitting alpha particles that can damage the DNA in dividing lung cells. Cells regularly repair such damage to DNA, but not always. In those cases, cancer can result. Approximately 150 000 lung-cancer deaths occur each year in the United States. It is estimated that about 18 000 of these may result from radon exposure. *But* it is smokers and people in homes with smokers who bear the brunt of the risk. This is because the radon daughters (^{218}Po and ^{214}Po) attach to tobacco particles, and are inhaled into the lungs and trapped.

Box 17.2 Most exposure to ionizing radiation is natural

About 80% of the exposure to ionizing radiation in the United States is natural for the average person. ■ Radon is responsible for about 55% (Figure 17.4). The actual percentage for which radon is responsible is higher or lower depending upon the radon level in your surroundings. ■ Another 11% of natural exposure arises from radioactive elements within our bodies such as *carbon-14* (^{14}C) and *potassium-40* (^{40}K). In fact, about 1 in every 10 000 potassium atoms in our bodies is radioactive. ■ Terrestrial sources, rocks and soils, provide another 8% of natural exposure. Uranium-238 is the largest terrestrial source. *Thorium-232* and potassium-40 contribute lesser amounts. ■ Another 8% of natural exposure to ionizing radiation comes from cosmic rays (the electrons, protons, and photons that enter Earth's atmosphere from outer space[4]). About 300 cosmic rays per second pass through your body if you live at sea level. Those living at higher altitudes have higher cosmic exposures, and aircraft crews and passengers experience higher levels still. Just as occurs with industrial pollutants, natural radioactive elements also find their way into water, air, and food.

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[4] Cosmic rays react with elements in the Earth's atmosphere to form ^{14}C and ^{3}H (hydrogen-3, or tritium). ^{14}C and ^{3}H settle to Earth and find their way into plants and animals. ^{14}C dating is often used to determine the age of once-living plants and animals.

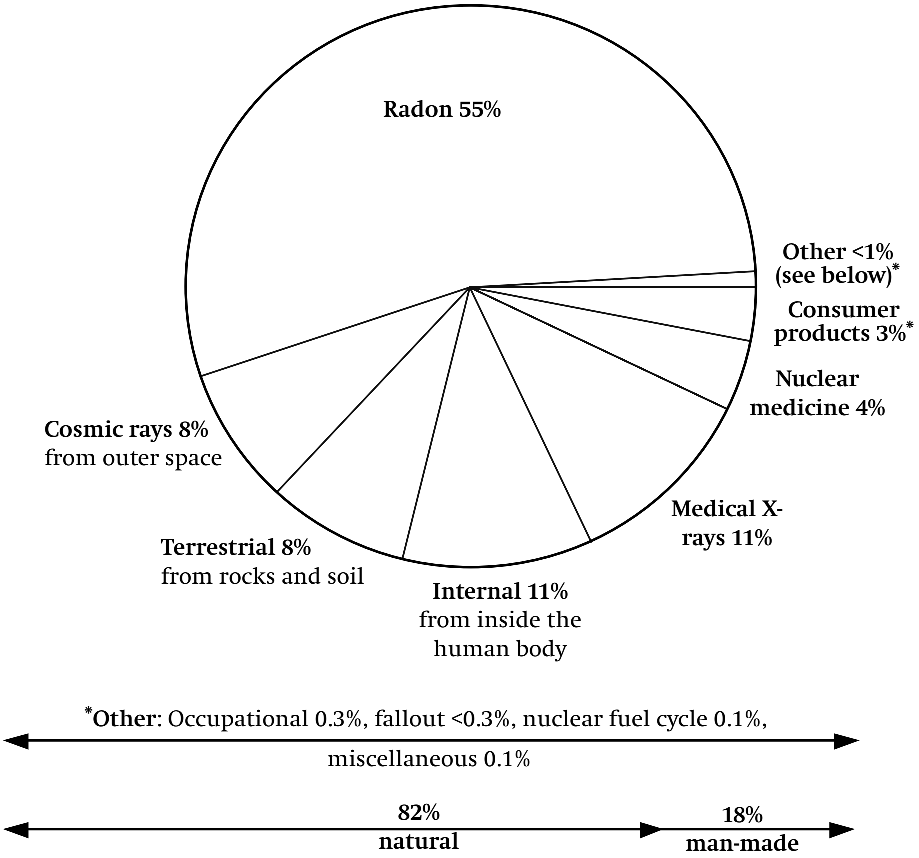

Figure 17.4 Sources of ionizing radiation exposure to the US population

Even homes with average radon levels engender interesting comparisons. Because of radon, the average nuclear-plant worker goes home to higher levels of radioactivity than experienced at work. Indeed, radon first began to receive major attention in 1984 when engineer Stanley Watras, set off an alarm at a nuclear power plant in Pennsylvania – he was radioactive. Investigation revealed the source was his home, which had 4400 pCi/l radon in his cellar, 3200 pCi/l in the living room, and 1800 pCi/l in the bedrooms – thousands of times greater than an average home. Nonetheless, it was possible to remediate the home and the Watras family moved back into it.[5]

Human-generated sources

Ionizing radiation produced by human activities represents only about 18% of the average person's total exposure. ■ About 83% results from medical diagnostic procedures, especially X-rays used for chest and dental examinations and

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[5] Materials taken from the Earth also contain radioisotopes; coal is one. As it burns, radioactive elements escape into the atmosphere. Residents near a coal-burning power plant have higher exposure to radioactivity than do those living near nuclear power plants, where emissions are more tightly controlled. Steam from geothermal energy also contains radioactive substances. Phosphate rock, used in fertilizers, contains higher levels of uranium than does surface soil. Groundwater contains higher levels of radioactivity than surface water.

mammograms. ■ Most of the remaining 17% comes from building materials and consumer products. ■ The other 1% of exposure results from (all taken together), occupational exposure, nuclear fallout, and nuclear power.

Detecting and reducing radon

Air

Homeowners can test the radon levels in the air in their homes. A test kit, typically a canister of activated charcoal is left open to the air for 2 to 7 days. It is then sealed, and mailed as directed on the kit to a laboratory. After analysis, results are sent to the homeowner. If the reading is high, the result needs to be confirmed through a longer-term test. Some states require radon testing before a home is sold. ■ A number of factors affect the radon concentration in indoor air. Levels are lower in summer, when a house is more open, so testing is done in winter to find the highest levels. ■ Radon levels can sometimes be much reduced simply by sealing openings in basement floors. Or radon can be diverted by installing a pipe below the basement; this pipe extends up the house walls and vents to the outside with the assistance of a suction fan. Those building a new home can take preventive action by installing a diversion system when the home is built. In locales with high potential for radon, the EPA encourages builders of new homes to install a passive, radon-control system.

Water

A second source of radon in the home is well water, especially water from a deep well. The amount entering the home in municipal tap water is typically lower, even if its source is groundwater. This is true because radon escapes into the air during processing. Showering and other uses of water in a home allow some radon to escape into indoor air. However, only about 1 molecule in 10 000 molecules in water escapes. This amounts to only 1% to 2% of radon in the air in a home.[6] There is an exception: radon can build to high levels in a closed bathroom during showering, but the exposure time is short. Despite the small amount escaping, risk assessment estimates that radon from water causes 160 lung-cancer deaths a year, about 1% of the lung cancers attributed to radon in air. Also, people who drink water with high radon levels run a slightly greater risk of stomach cancer. An estimated 20 cases out of 13 000 stomach-cancer deaths in the United States each year may be due to radon in drinking water.

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[6] A few years ago, the EPA proposed a maximum contaminant level (MCL) for radon in water of 300 pCi/l. This would have required municipal water suppliers with levels higher than 300 pCi/l to reduce them. The proposed MCL was later dropped, but it represents an interesting case: the EPA estimated that an additional 160 lung-cancer deaths per year in the United States result from radon that has escaped into air from water. *This risk is greater than that for any other contaminant in the water supply that is regulated by* the *EPA*. Some expressed concern that if we do not regulate radon then industry could claim that, because the pollutants it releases into water present a smaller risk than radon they should not be regulated either. Others countered that society has the right to expect industrial emissions to be more strictly controlled than natural ones.

- The greatest risk by far comes from radon that seeps from the ground into indoor air. Smokers and their families bear a disproportionate amount of that risk.

Box 17.3 | Radon and scientific uncertainty

What could be less controversial than urging people to measure radon levels in their home and to remediate high levels? Scientific groups including a National Academy of Sciences panel agreed that radon causes lung cancer in humans. Unlike most other carcinogens, for which only animal data are available, we have human information for radon. The association between radon and lung cancer seems clear. *However*, the association was made by studying miners who had worked in years prior to the introduction of modern ventilation. Those mines contained radon levels hundreds or thousands of times higher than those in most homes. Most miners smoked too. Moreover, the mines were extremely dusty. Thus, some scientists doubt that lung-cancer deaths among such workers can be extrapolated to the conditions of average homes. Many studies have looked for relationships between radon levels in homes and lung-cancer incidence. The conclusion that most scientists reached is that smokers and those that live with them bear most of the radon risk. Assuming this is true some argue that the EPA should concern itself only with homes with much higher radon levels where even non-smokers could be at risk, at least 20 pCi/l of radon. In the United States this is an estimated 50 000 homes. The EPA reminds skeptics that no amount of ionizing radiation is free of risk, and that about 700 deaths a year in the United States are attributed to even the low levels of radon in outside air.[7]

Questions 17.1

1. Are you concerned about radon in your home? Explain.
2. Before buying a home, will you ask that it be tested for radon? Explain.
3. What would the radon level need to be in the air in your home before you would remediate it? Why did you choose this level?
4. (a) If small children lived in the home, would you be comfortable if they regularly played in a basement not tested for radon? (b) If the children only occasionally played there, would that affect your concern?

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[7] Recall that for chemicals, an increasing dose has an increasing effect. This holds for radioactivity too. In the mid-1990s, investigators reanalyzed lung-cancer deaths among uranium miners exposed to radon, pooling data from 11 studies covering 2700 lung-cancer deaths among 65 000 miners. They found that as the miners' exposure to radon increased, so did lung-cancer risk. Their results suggested that even average home radon levels pose some risk. The study also found that long-term exposures to low doses of radiation – a condition similar to that found in homes – was more risky than short-term exposure to high doses. The authors understood the difficulty of extrapolating from conditions found in mines to those in homes, but still recommended remediation of homes with radon levels greater than the EPA's action level of 4 pCi/l. National Library of Medicine, Medline Abstract. 2004. Lung cancer in radon-exposed miners and estimation of risk from indoor exposure. http://www.jncicancerspectrum. oupjournals.org/cgi/medline/pmid;7791231 (accessed January, 2004).

Indoor air of impoverished homes

For literally billions of impoverished people in countries as far apart as Bolivia, Kenya, and China, indoor air poses no uncertainty – it is a major health risk. The worst offender is smoke. Fuel is burned inside homes with little or no ventilation, especially in cold weather. People burn wood, straw, or dried manure, although rural Chinese most often burn coal. Those suffering the greatest exposures to particulates are women as they cook and their children. Not surprisingly, respiratory diseases are commonplace, often severe. Worldwide each year, acute respiratory disease causes millions of deaths in children under 5 years old.

These fuels are often used for heating too, so adult males are also affected. Chronic bronchitis is common among all adults. In China, where about 800 million people burn coal, the problem has an added dimension. Individuals also suffer from the fact that some coals burned contain as much as 35 000 ppm arsenic and many are also high in fluorine. Thousands have developed severe arsenic poisoning and millions fluorine poisoning. Other coals have toxic levels of other elements such as mercury. Lung-cancer rates are also very high.

Simple technologies can make a major difference in impoverished locales. ■ A cooperative project between Beijing's Chinese Academy of Preventive Medicine and the US EPA found that replacing poorly ventilated stoves with well-ventilated stoves resulted both in reduced soot and smoke in the air, and a dramatic reduction in lung-cancer rates. ■ In Kenya, a project gave women stoves. The replacement stoves, although simple in design, burned more efficiently than traditional stoves, emitting much less smoke and burning 40% less fuel. Thus, they not only improved respiratory health, but saved women hours a day previously spent in collecting biomass fuel. At the same time, scarce biomass such as wood was conserved. ■ In China's Yunan Province the Nature Conservancy works with the Chinese government and villages to produce biogas (methane) from manure. In the mountain village of Haixi, they set up a demonstration project: animal manure and human waste is loaded into a lined pit, and a greenhouse built over it; heat generated from the digesting manure warms the greenhouse, which grows vegetables for villagers. *In addition*, the fermenting manure emits methane, which is piped into an adjacent schoolhouse. Teachers previously cooked children's lunch over wood fires with not even windows open in this cold climate. Now they use instead a biogas stove with the much more clean-burning methane. After the waste has finished fermenting and producing methane, it becomes fertilizer. Following this successful demonstration, individual villagers dug their own household fermentation pits, and were given help toward the $170 cost. Over 1 year, one cow's manure provides energy equivalent to 135 gallons (510 l) of gasoline. Some villagers still burn wood. These have been assisted with more-energy-efficient stoves that are vented to the outside. The project is spreading to other villages. With less need for wood, deforestation in the area is reduced as well as indoor air pollution.

These projects demonstrate what can be done. However, many hundreds of millions of additional people need assistance.

SECTION II

Hazardous household products

About 1.5 million Americans visit hospital emergency rooms each year because of poisonings or possible poisonings. About 10% are admitted into the hospital. More than 80% of the cases are among children less than 6 years of age. These figures do not include the many people who have had reactions to hazardous household products such as pesticides, solvents, ammonia, or chlorine, but do not report them. In addition to poisonings, exposures to some household products are responsible for injuries to the skin, and eyes.

How household products concern us

The words, “toxic,” “corrosive,” “flammable,” and “reactive” were introduced in Chapter 12 to describe characteristics of industrial hazardous waste. Some household products have the same characteristics.

Corrosive products

These can directly damage (corrode) the skin, eyes, or mouth. Examples are products containing alkali (lye) such as drain openers or oven cleaners. Corrosive products often have the word “poison” on the label and the word “danger.” Emergency-room visits for treatment of skin or eye injuries resulting from improper use of corrosives are common. ■ Diluted with water, a corrosive substance may only be an irritant. A very dilute corrosive may present no hazard at all. Although an irritant is less dangerous for most people, it may nonetheless cause skin redness, itching, or rashes. Cleaners, cosmetics, metals, and polishes are sometimes irritants. ■ An irritant is a greater problem when a person becomes *sensitized* to it after repeated use, and suffers more-severe reactions. Since latex gloves have come into common use, many people have become sensitized to latex.

Toxic products

Household products can be toxic. Because all substances are toxic in high doses, treat all products, including vitamins, minerals, aspirin, and laxatives, with care. This is especially important if children are in the home. However, only a few household products are legally poisons, and they are clearly labeled. They include oxalic acid, found in a few cleaning products, and methanol, found in windshield washing fluids. Most pesticides available to householders are less toxic than those used by professional applicators and are not considered poisons. Nonetheless, home pesticide poisonings occur, and children are particularly vulnerable. ■ Toxicity information on the label refers to acute toxicity, an adverse health effect occurring soon after exposure. The label does not –often cannot – provide information on possible chronic toxicity. Significantly, although home-use pesticides may be relatively safe for humans, creatures such as birds, earthworms, or bees can be poisoned.

Flammable products

A flammable product can catch on fire easily. Household products that contain petroleum distillates are flammable. Examples are oil-based paints, paint thinners, paint strippers, certain furniture and floor polishes, and some rug cleaners. Products that contain organic solvents are often flammable, and many aerosol sprays use flammable hydrocarbons as propellants. A *combustible* substance is similar to a *flammable* one except that it does not catch on fire as readily.

Reactive products

Well-known reactive substances are dynamite, gun powder, and firecrackers. Household products may be reactive too. Dry and liquid bleaches that contain chlorine will, if mixed with household ammonia, give off highly irritating and toxic fumes. Chlorine also reacts with acid-containing products such as some toilet and tile cleaners. Even some dish-washing detergents contain ammonia and should not be mixed with chlorine-containing products. ■ A general rule is, don't mix any chemical products. Overheated or accidentally punctured aerosol cans may be reactive in a different way, they may explode.

No radioactive products

TV sets emit small amounts of ionizing radiation. Other materials that emit higher background levels of ionizing radiation than wood are building materials coming from the earth, including granite, other rock, and soil. We do not ordinarily find radioactive substances in the items around us except for tiny amounts in some smoke detectors, exit signs, and Coleman-lamp mantles. As noted above, our exposure to radioactive substances or ionizing radiation is almost all from natural sources.

Some products have more than one hazard

A product may have more than one hazard. A prominent example is gasoline. It is flammable and explosive, its fumes are toxic, and it is a skin irritant. Young people who inhale gasoline fumes for a "high" continue to be poisoned or killed by this practice. Another hazard is accidentally aspirating gasoline into the lungs when sucking it from a motor vehicle's fuel tank. Even small amounts in the lungs can be disabling. These same hazards are present in other products that contain petroleum distillates or organic solvents.

Figure 17.5 Read product labels. Credit: US EPA

Labeling laws

A century ago about 500 American children a year, mostly under 5 years old, reportedly died in accidental home poisonings. Thousands more were burned by the lye (caustic) used to make household soap. This situation changed in 1927 after Congress passed the Caustic Poison Act. This required that containers of caustic be labeled. In 1960, a law applying to all hazardous products sold to householders was passed, the Hazardous Substances Labeling Act. Finally in 1970, the Poison Prevention Act, requiring child-proof containers for certain hazardous substances became law. By the beginning of the twenty-first century, although the US population has greatly increased, many fewer children die from poisoning. But we still purchase hazardous products from grocery, hardware, discount, craft and hobby, agricultural product, and drug stores. Almost any store may sell products containing hazardous ingredients.

Information required on product labels follows.

- One or more *signal words*: "poison," "danger," "warning," or "caution."
- Its *principal hazard*: is it flammable, harmful or fatal if swallowed, skin and eye irritant, or vapor harmful?
- The *common or chemical name* for the hazardous ingredients.
- The *name and address* of the product's manufacturer or distributor.
- *Statement*: Keep Out of Reach of Children, or equivalent statement.
- *Precautionary measures* are instructions for safe use of the product.
- *First-aid* instructions are often on the label, but may be inadequate. Call the Poison Control Center if an accident occurs.

Read the label

Look for signal words on a product's label (*poison, danger, warning, caution*). Look especially for the word poison or danger. "Poison" indicates the greatest level of toxicity whereas "danger" may refer to a corrosive, flammable, reactive, or toxic substance. The US EPA has a Read the Label First campaign to promote basic safety in the use of pesticides and other products (see Figure 17.5).

■ "Caution" indicates a low-hazard product. Detergents commonly have the signal word caution on the label, but still lead to home poisoning incidents. Small children are especially likely to ingest them. Fortunately, taste and low toxicity prevents most incidents involving detergent ingestion from being serious. Liquid household cleansers often give off VOCs, enough to lead to adverse reactions if too heavily applied in a closed space. ■ Labels on pesticides are covered by the Federal Insecticide Fungicide and Rodenticide Act (FIFRA), not the Hazardous Substances Labeling Act. For pesticides, "poison" indicates the most toxic product, "warning" refers to medium toxicity, and "caution" to the least toxic product.

■ *Active ingredients* are those that carry out the function that the product is designed to do. Its *inert* ingredients carry the active ingredient, or make it easy to apply. However, some inert chemicals are hazardous too. ■ Sometimes the word "non-toxic" is found on a label, but non-toxic has no legal meaning. Any substance can be toxic in high-enough doses. Nonetheless, a product labeled non-toxic is probably less toxic. Otherwise, a signal word would be on the label. ■ Some terms on labels such as *petroleum distillates* are generic. A petroleum distillate contains chemicals produced during petroleum cracking. ■ *Organic solvent* is also generic. It may refer to acetone, isopropyl alcohol, methylene chloride, or another solvent.

Reducing exposure to hazardous products

Toxics use reduction (TUR)

TUR is a type of P^2 that refers to reducing exposure to hazardous substances by eliminating or reducing their use. The first steps for individuals to take to protect themselves are: ■ Read the label. ■ Follow directions on the label. ■ Minimize use of especially hazardous products.

If you need to use a hazardous product: ■ Handle it in a way that minimizes exposure. ■ Use the minimum amount necessary to do the job. ■ Use plentiful ventilation. ■ Do not use aerosol products, or even fairly innocuous products, in closed rooms. ■ Use an exhaust fan to remove fumes from petroleum-based products such as paints or shellacs. Even for latex paint, provide plenty of fresh air. ■ To strip paint from furniture, wait for summer and do it outside. ■ Get in the habit of using gloves and safety glasses. ■ Don't mix chemical products; in particular, never mix bleach and ammonia. ■ Keep chemical products away from children, including detergents, and vitamin and mineral supplements. ■ *Always* keep products in original containers, even if only adults are around.

Alternatives

Alternatives to products with the signal word *danger* or *poison* are usually available. If children use glue, buy glue with the word "non-toxic" on the label. For paint, use water-based (latex) rather than oil-based paint when possible. Table 17.2 shows some alternative cleaning products described by the Air and Waste Management Association that don't emit VOCs. However, one alternative noted is household ammonia; this is an inorganic chemical that emits strong acrid fumes that can irritate the lungs, skin, and eyes.

Hazards from earlier years

Some hazards are unique to older homes, especially asbestos and lead paint.

Asbestos

Asbestos is a naturally occurring fibrous mineral. Because of its heat resistance, asbestos was widely used to insulate furnaces and furnace pipes. It is still often found in old homes and buildings. Flaking asbestos poses the greatest danger as its particles can become airborne, and may be inhaled. Asbestos was also a component of less-problematic products such as floor and ceiling tiles, fireplace gloves, and ironing-board covers. *Chrysotile asbestos*, which is considered less

Table 17.2 Alternative household cleaning products

- **All-purpose cleaner**: 1 gallon hot water, 2/3 cup baking soda, 1/4 cup ammonia, 1/4 cup vinegar. (Make the solution stronger by doubling all ingredients except water.)
- **Window cleaner**: mix 1/4 cup ammonia with 1 quart water.
- **Furniture polish**: mix 1 teaspoon lemon oil and 1 pint mineral oil.
- **Oven cleaner**: wash the oven frequently with a mixture of warm water and baking soda. Soften burned-on spills by placing a small pan of ammonia in the oven overnight. Sprinkle salt onto fresh grease spills and then wipe clean.
- **Toilet cleaner**: use baking soda, a mild detergent, and a toilet brush.
- **Floor polish**: polish floors with soda water.
- **Silver cleaner**: to a small pan of warm water add 1 teaspoon baking soda, 1 teaspoon salt, and a 2 × 2 ft piece of aluminum foil. Soak silverware overnight.
- **Rug cleaner**: sprinkle cornstarch on carpets and vacuum.
- **Drain opener**: to loosen blocked drains, spoon a tablespoon of baking soda into drain, and then slowly add 1/3 cup white vinegar. Use a plunger to get rid of the loosened blockage. Prevent blockages by pouring boiling water down drains once a week, using drain strainers, and not pouring grease down drains.
- **Moth balls**: place cedar chips or blocks in closets and drawers.
- **Insecticides**: wipe houseplant leaves with soapy water.

Credit: Air and Waste Management Association (http://www.awma.org/resources/education/indoorair.htm).

dangerous than *amphibole asbestos* was used in most buildings and homes. Removing asbestos from heating systems is not recommended unless it is deteriorating because the removal process releases asbestos fibers into the air. Instead, ask a professional how best to maintain it in place. Professionals are also needed to assess whether asbestos is present in old tiles. Leave asbestos-containing tiles in place unless they are deteriorating. Repair or removal of asbestos-containing materials should be done by an EPA-approved professional. Exposure to asbestos, especially at levels found in industrial settings, is associated with asbestosis, lung cancer, and mesothelioma. Some risk is associated with ingesting asbestos in drinking water, but the primary risk is inhaling airborne fibers into the lungs, where they may become permanently trapped.

Lead

Leaded paint was once the paint of choice. Lead was added to paints in the United States for many years although in progressively lower amounts until its banning from indoor house paint in 1978. Highest levels are most often found in homes built before 1940. Local and state health departments can provide information on identifying lead paint. Tiny children may eat flaking lead paint from windowsills or woodwork and, of even greater concern, they may inhale dust in homes with flaking leaded paint. Vacuuming the home may exhaust the lead-containing particles back into household air. Unless an especially equipped vacuum cleaner is available, a better method is using wet cloths and mops. As with asbestos, if the lead paint is in good condition, leave it undisturbed. Cover it with wallpaper or another covering. If painted woodwork is in good condition, wipe it frequently with a wet cloth to lessen the chance of lead dust entering the air. If small children live in the home, consider asking a professional to remove the paint from the woodwork or replace the woodwork. Homeowners should not remove leaded paint themselves. Soil around old houses often contains high lead levels, which can be tracked into the home on footwear.

Household hazardous waste

Residues of household hazardous products become *household hazardous waste* (HHW). Waste paint features prominently in HHW. Other products are paint thinners and strippers, pesticides, cleaners and polishes that contain petroleum distillates, and alkaline drain and oven cleaners. Even some discarded cosmetics, such as acetone nail-polish remover contribute small amounts to HHW. Creation of HHW can be prevented by buying the smallest amount of a product that can do the job desired. This is one time to avoid economy sizes. Once a hazardous product is purchased, use it all or give it to someone who will. If residues remain, dispose of them carefully. For example, dry out waste paint in a place safely away from children before disposing of it. Sometimes product labels have disposal instructions or a telephone number to call for more information on the product. A minority of communities in the United States have HHW collection programs.

Paint

About half of all HHW is paint. Water-based (latex) paint is less hazardous than oil-based paint. Alternative “natural” paints containing beeswax, plant waxes, and linseed oil are available, but check the labels for expiration dates. Respect those dates because some can, literally, rot. Buy only the amount of paint needed. If the leftovers are usable, give it away. Encourage your community and state to adopt a paint recycling program or a paint “drop and swap.”

Used oil and antifreeze

■ Another HHW produced in large volumes is familiar to those who change their own car oil. This is *used oil*, which is both ignitable and toxic. Never pour used oil on the ground or down a drain, either in the home or a storm drain. Check with your city office for locations that take used oil. The EPA could regulate used oil as hazardous waste, but millions of do-it-yourselfers make this impractical. Instead, the EPA developed standards for commercial handlers of used oil: if the oil is destined for disposal, it may have to follow hazardous-waste regulations. However, if it will be recycled, it is treated less strictly.

■ Antifreeze too should never be poured on the ground or the driveway. It is sweet tasting and can poison animals and children. Some brands have a bitter-tasting additive to discourage ingestion. Contact the local wastewater-treatment plant to inquire if it can handle antifreeze. If so, *little by little* flush the antifreeze down the toilet. Don’t pour antifreeze down the drain if the home has a septic system, as it may kill the system’s microorganisms.

Pesticides

About 95% of American households use pesticides, commonly moth repellents, pet flea collars, no-pest strips, lawn and garden pesticides, and disinfectants. Pesticides available to householders are ordinarily less hazardous than commercial pesticides. However, pesticides may be blown by wind or carried off with rainwater into other people's yards or into a local stream or lake. They reportedly cause many bird deaths, and can kill beneficial insects such as honeybees. Picked up on footwear and tracked into homes, pesticide residues are detected on carpets even in homes not using pesticides. ■ The person most highly exposed to the pesticide is usually the one applying it, but others within the home and yard are also exposed.

Pollution prevention, P^2 can effectively reduce pesticide use within the home. ■ Eliminate the food particles that attract cockroaches and ants. Use containers with tight-fitting lids to store food. Fill in cracks that allow cockroaches and other pests to enter the home. A fly swatter can sometimes replace an insecticide. "Natural" repellents are sometimes useful. Boric acid is useful for cockroach and ant control and is less toxic than many other pesticides. Some people report that cedar chips in their dog's bed prevent fleas, and that pyrethrum-daisy flowers deter moths. To prevent attracting moths, store clothing clean and so avoid the use of moth balls. In a home with carpets or small children, leave shoes at the door to prevent tracking of pesticides into the home. ■ Outside, why not allow dandelions, clover, and other "weeds" to inhabit the lawn rather than using herbicides. In the garden, read up on companion planting as a means to deter predators, and lower pest populations by rotating crops from year to year. Reduce places with free-standing water that can allow pests to multiply easily.

If a pesticide is needed, control measures are important: buy the smallest amount that will do the job; read the label and follow directions. If a spray is used, buy a pump, not aerosol. The latter produces tiny particles, which can be inhaled deeply into the lungs. If used within the home, make sure ventilation is good. Check if gloves are needed. Pay attention how long after spraying a treated area should be avoided. In particular, consider how to protect children in the area. ■ Dr. Michael Shelby of the National Institute of Environmental Health Sciences recommends the following for pesticides: "The best advice for anyone, and my advice at home for my wife and children, is (1) don't overuse them; (2) don't expose yourself to them, or if you do, do it at absolute minimal levels; and (3) keep them in a safe place where animals and children cannot get to them."

HHW collection programs

In the hands of a householder, HHW is not regulated as hazardous waste. However, once it passes into the hands of a collection program, it is strictly regulated. Thus, community HHW collection programs have been expensive and sometimes a liability to the community. The EPA wanted to change this and encourage recycling components of HHW such as batteries and mercury-containing thermometers. It no longer subjects voluntary programs to regulations regarding collection, storage, and transportation of some HHW components. However, the waste must be either recycled or properly treated before disposal.

Questions 17.2

1. What information is of most interest to you when you look at a product's label? Why?
2. (a) Under what circumstances do you use pesticides inside and outside your home? (b) Are there chemical products you would never have in your home? Explain.
3. Assume you found an *old* house that you want to buy. What environmental hazards would you check the home for: (a) In its interior (including basement and attic)? (b) In the heating system? (c) In the plumbing system? (d) In its outbuildings and land?
4. Answer question 3 again, but this time for a home that is less than 10 years old.
5. (a) Do emissions from new carpets, drapes, or wood paneling concern you enough that you would only install these during the summer? Explain. (b) Would you apply paint or varnish to the inside of your home in the winter? Explain.
6. As you shower or otherwise use water, what water pollutants may become airborne: (a) In a home served by municipal water? (b) In one with well water?

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Chapter 18

Zero waste, zero emissions

> "The time has come for humankind not to expect the Earth to produce more, but rather to do more with what the Earth already produces."
>
> *Belgium industrialist, Gunter Pauli*

How can we speak of zero waste or zero emissions if, as you learned earlier no process is 100% efficient? The answer is that *zero waste* is a philosophy, one that says there is no waste: what we call "waste" or "pollutant" is really a useful resource. This philosophy recognizes too that, if we aspire to reduce waste by 100%, we accomplish more than if our goal was 40% or 80%.

Sections I to III below emphasize *dematerialization*, reducing the quantities of materials we use. **Section I** asks how well we are doing in reducing waste and pollution, and looks at the waste that the United States produces. **Section II** discusses *industrial ecology*, a discipline with the goal of enmeshing industrial society into the environment. It also raises the idea of increasing our efficiency in resource use 4-fold, perhaps as much as 10- to 20-fold. **Section III** examines tools useful in working toward zero waste, including life-cycle assessment (LCA) and design for the environment (DfE). Other tools too point toward ways to reduce use of resources: *servicizing* and *product stewardship*. **Section IV** takes us to *detoxification*; that is, changing the chemicals we use and how we produce them, "green chemistry." The intention is to reduce chemical risk to humans and the environment. Finally, **Section V** asks, is there progress toward zero waste? Who is making advances toward zero waste, programs such as Xerox's *Xero-waste*, the city of Canberra, and countries including Canada working toward *Target Zero*.

SECTION I

Waste and emissions

Pollution has been alleviated in industrialized countries – up to a point. Look at examples. ■ Air. Collectively, emissions of major air pollutants[1] in the United States have fallen 25% since 1970. This improvement occurred despite a 161% increase in gross domestic product and a 149% increase in vehicle miles traveled. Despite these advances, 133 million people live in areas where standards set to protect human health are exceeded for one or more major air pollutant. Ground-level ozone remains high enough to affect health in many cities. Sulfur dioxide and nitrogen oxide emissions, although lower, are high enough that acid deposition is worsening in some locales. ■ Water. Since 1970 the percentage of fishable–swimmable waters almost doubled. Yet about 40% of waterways are still not fishable and swimmable. In addition, non-point-source runoff into streams, lakes, and estuaries continues to be poorly controlled. Like the United States, other prosperous countries have cleaned up their environments in many ways.

Worldwide the picture is sobering – recall Table 2.1. The Asian Development Bank in 2002 issued a statement reporting that, "environmental degradation – air pollution, biodiversity loss, land degradation, exhaustion of aquifers, water pollution, and exposure to hazardous waste – is now 'pervasive, accelerating and unabated.'" Equally serious problems exist in Africa and parts of Eastern Europe. These issues are important to the people immediately affected, and also to all of us.[2]

Meanwhile, the complexity of environmental problems increases and, as population and development continue to rise, the problems will worsen without decisive action. What is needed? First steps would be to greatly increase citizens' environmental awareness and the will of governments to act. Resources necessary to solve environmental problems are sorely lacking in many poor countries. Nonetheless, as seen below, progress, although unsystematic is being made. We may not reach the elusive zero; however, providing ourselves with a mindset of zero, it is possible to achieve surprising reductions even in resource-poor societies.

How much waste?

The United States alone generates about 10 billion tons (9.1 billion tonnes) of waste per year (Figure 18.1), much as contaminated

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[1] These collective pollutants are the VOCs plus the six criteria air pollutants (carbon monoxide, lead, sulfur dioxide, nitrogen oxides, ground-level ozone, particulate matter).

[2] Responding to its own assessment, the Asian Development Bank adopted a 5-point policy: reduce poverty, take the environment into account in its own operations and when addressing economic growth, promote regional and global cooperation, find partners to help in reversing environmental degradation.

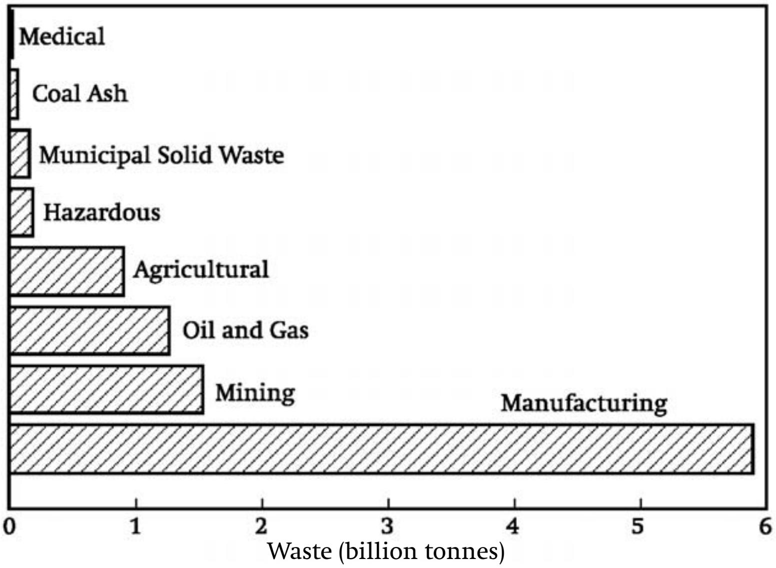

Figure 18.1 Waste generated in the United States (billions of tonnes).[3] Source: US Congress, OTA. *Managing Industrial Solid Wastes from Manufacturing, Mining, Oil, and Gas Production, and Utility Coal Combustion*, Report No. OTA-BP-O-82. (Washington, DC: US Government Printing Office, 1992)

water.[3] Some is from mining operations, oil and gas recovery, and agriculture. However, considered by weight, most is manufacturing waste produced as we make a multitude of products from chemicals to computers, bread to cigarettes, automobiles to clothing, and so much more. You can see that if we are generating so much waste, we are obviously also using earth's resources. How can we cut resource use, how can we *dematerialize* our societies?

SECTION II

Industrial ecology

Industrial ecology (IE) is sometimes called the science of sustainability.[4] Quite a new concept, IE still lacks precise definition. But, its goal is ambitious: enmesh our industrial society seamlessly into the environment – establish a framework in which industrial society and

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[3] The Office of Technology Assessment (OTA) report notes that a large fraction of the total weight in the industrial categories is water. Dry weight of industrial wastes may be as low as 10% of the total.

[4] What does sustainability mean? In 1987, a different term, "sustainable development," was defined as meeting the needs of today without compromising the ability of future generations to meet their needs (report of the UN-sponsored World Commission on Environment and Development). What sustainable development means in daily practice is difficult to define, and the subject of discussion, even controversy: to what extent can we have an impact on our environment without harming its ability to provide natural services such as water and air purification, pollination, soil fertility, decay of organic materials in the environment, and many others? There are other frameworks for looking at a sustainable world. An approach called "sustainability science" emphasizes economic and social sustainability as part of a sustainable environment. Industrial ecologists also believe in the great importance of economic and social sustainability.

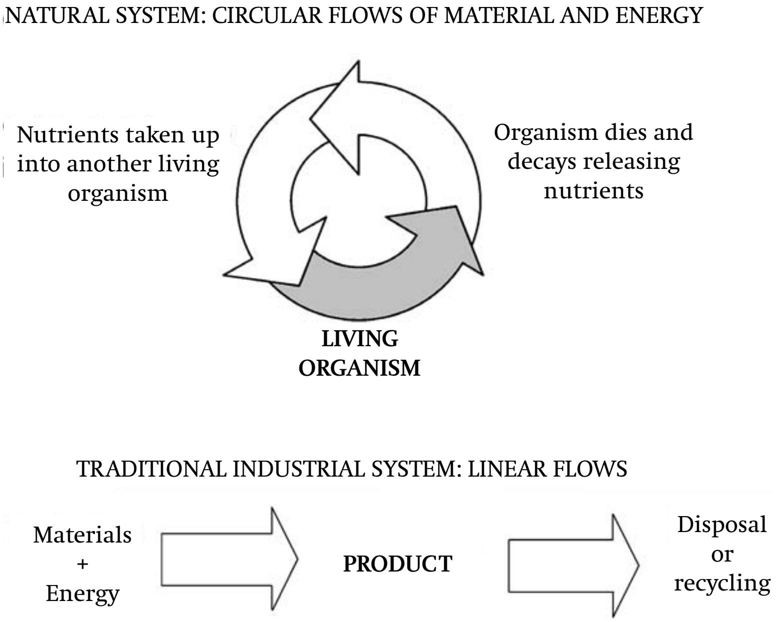

Figure 18.2 Natural and industrial flows of materials and energy

ecosystems function together holistically. Instead of being isolated from the living world industrial society will be part of it working in concert with other life. Think of industrial society as including beyond manufacturing, agriculture, energy production and use, transportation, and other activities.

To move toward this almost visionary end, we need tools. Important tools do exist. One is life-cycle assessment (LCA). LCA allows us to study the flows of materials and energy that occur throughout the life of a particular product (or process such as fossil-fuel combustion).[5] Once flows are fairly well understood, another tool, design for the environment (DfE), is available to help redesign the product or process. An important part of DfE – certainly in the longer term – is to design systems that mimic nature, become more like biological systems. Other tools in a move toward sustainability include extended producer responsibility and servicizing, described below.

Becoming closed-loop systems

One author stated, “the ultimate goal of industrial ecology is bringing the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials.” A major characteristic of biological systems is that they work within closed loops (Figure 18.2). The wastes that living creatures excrete are degraded

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[5] The sun provides the energy to operate natural systems. A plant or a photosynthetic microbe directly captures the sun’s energy. An animal obtains energy indirectly from eating plants or eating other animals. Human industrial systems depend on the sun too – our oil, coal, and gas initially came from living plants. Solar panels also use the sun directly. Wind turbines are powered indirectly by the sun’s effects on the climate etc.

and become nutrients to living organisms. Likewise, when living creatures die, be they plants, animals, or bacteria, they too biodegrade to nutrients. So, for industrial ecology to succeed, we must find ways to mimic nature, to transform society's activities into closed loops that do not damage the natural world. This future world would create useable byproducts, not wastes. You have already seen one early example of recycling "pollutants" and "wastes" in Kalundborg (Figure 2.2). In closed-loop systems, byproducts continuously recycle within closed loops. We could still discard biodegradable materials under circumstances where we know they will biodegrade without harming the environment. There have been attempts to set up closed-loop systems experimentally. See Box 18.1 and remember Biosphere 2 (Box 1.1).

Box 18.1 Space ecology

Manned space flights store their wastes and bring them back to Earth. This would be impractical for long-term missions. In 1978, NASA began studying a self-sustained system for living in space, an "advanced life-support system." Long-term flights would need systems to produce food, purify water, regenerate oxygen, and prevent pollutants from building up in the air – they needed closed-loop systems. Green plants would be grown as food. Plants would also absorb the carbon dioxide that humans respire, while emitting the oxygen that humans need. Plant transpiration would provide pure water. Plant and human wastes would be resources. In addition, "All systems would have to operate under the restrictions of minimizing volume, mass, energy, and labor." A computer would integrate this complex system, which would first need extensive testing on earth. Knowledge gained in developing this system would have applications not only in space, but on an Earth that contains more human beings, more wastes, and fewer virgin resources. Both Biosphere 2 and the NASA program teach us more about how natural systems work. They begin to help clarify how we must adapt ourselves to nature rather than continuing in our naïve expectation that nature can boundlessly adapt to humans.

Today's recycling is not enough

Recycling as described in Chapters 2 and 11 only *slows* the linear flow of materials. Industrial symbiosis (Chapter 2) is a great improvement, but needs to be applied much more widely and to all kinds of industrial systems. As architect William McDonough stated, "We should recycle, but it is not the first thing we should do, it is the last. Redesign first, then reduce, and finally recycle, if there is no other alternative."

Can we use resources ten times more efficiently?

To achieve closed-loop systems we must use resources with much greater efficiency; that is, we must use less material and less energy. ■ Some believe that to maintain today's living standards we need a *factor ten* improvement in efficiency: we must produce the same amount of goods and services with 90% fewer resources. Others go further and think *factor twenty*. ■ Why would we need such dramatic increases in efficiency? One major reason is that our already large human population continues to grow. At the same time, literally billions of the world's people live in poverty, many in absolute poverty not knowing where their next meal is coming from. These people need more food and material goods. We need to increase not decrease economic activity to satisfy these needs. But if society attempts to do this using "business as usual" there will not be enough resources. Nor, most likely, will the environment continue to provide natural services efficiently. Because factor ten seems a daunting goal *factor four* is seen as a more reachable initial challenge.

How do we go about increasing efficiency by a factor of four? Instead of continually extracting virgin resources and discarding the products made from them, we reuse them in a continuous loop. In the process, we *dematerialize*; that is, use fewer materials.

- Think about a sofa. We could find ways to lessen the amount of energy needed to make the sofa. But how do we decrease the amount of material in a sofa? We could build a – still attractive – sofa that is very durable. People would be encouraged to keep it indefinitely, re-upholstering it as it ages, not replacing it. We would make all the sofa's components – its upholstery, foam, wood and metal – reusable and recyclable. And we would design it for disassembly so that when parts need replacing or the sofa is finally "discarded," we disassemble it into those parts. In other words, the sofa could have a very long life and material use would be greatly decreased; so would energy and water use.
- Apply this to a toaster. Work to find ways to furnish the metals going into the toaster in a less-energy-intensive way that generates less waste – even one day, no waste. We would recycle metals so intensively that there would be little need to mine new metals; and, as for the sofa, we design the toaster for durability and reusability of component parts.
- Intensive use of materials and energy may raise another problem: Can we maintain full employment, and maintain our economy with long-lived products? Intensive use of material, changing the way we manage materials, requires an evolution of thinking too.

Some products become more practical and desirable when their size is reduced. Consider our computers. Even if it had been possible 50 years ago to use a computer as a word processor, that computer would have filled a room. Remarkable advances in technology have made possible the micro computers of today, which use conspicuously less materials. Changing computer technology was not motivated by environmental reasons, but it shows us what can be accomplished. Today, we need to deliberately design for the environment (DfE), deliberately look for ways to use fewer material and energy resources to make a product. More dramatic still is the emerging field of nanotechnology, which has a vision of making machines the size of molecules. But we need not wait for nanotechnology to get started. Discussed below are some tools we can use to lessen material and energy use.[6]

SECTION III

Tools for a zero-waste society

We need tools to reduce the great quantities of waste that we produce. Pollution prevention (P^2) reduces, sometimes eliminates waste. P^2 provides creative ways to reduce emissions, while conserving energy, water, and materials. But P^2 seldom eliminates all waste and for the foreseeable future, societies will continue to produce waste. Here is where we must change our thinking: think of useful byproducts not wastes. We then ask: How can we use this byproduct? Better still, we plan ahead as to how all byproducts created during the manufacture of a product can be used. ■ Remember industrial symbiosis in which one facility's byproducts are fed to another facility (Figure 2.2). Byproducts, captured pollutants, energy, or water – do not become waste, but are used and preferably used in a closed-loop style.

Life-cycle assessment

To move toward industrial symbiosis and closed-loop recycling, we need to use DfE. But, before we can use DfE to reduce the environmental impact of a product, we need to know what those impacts are. To determine impacts, we use life-cycle assessment (LCA). What are the environmental impacts – over its entire life cycle – of a piece of paper, plastic bag, car, or food such as an apple?[7]

Look at the four life-cycle stages (center of Figure 18.3). (1) Acquiring the raw materials for the product. (2) Manufacturing it. (3) Using (and sometimes reusing) and maintaining the product. (4) Recycling or managing the product as waste at the end of its life. In *each* of the four stages we must ask about:

- Inputs (left of Figure 18.3): How much material, energy and water are used?
- Outputs (right of Figure 18.3): What are the air and water emissions, solid wastes, and byproducts?

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[6] However, although computers and other electronics are very small compared with their antecedents, each person in industrialized societies uses many more electronics, and discards them frequently as newer products with ever-increasing efficiency and attractive features replace them. This issue is partially dealt with in the European Union as it has begun to make manufacturers responsible for electronic products throughout their entire lives. This stimulates DfE. However, it does not address the issue of our apparent insatiable need for more and more material products.

[7] Industrial ecology (IE) studies material and energy flows of industrial, consumer, and other "industrial" activities, and examines the environmental impacts of these flows; thus LCA is a basic tool of IE. It studies too how economic, political, regulatory, and social factors affect resource flows and how resources are used and transformed. The goal of IE is to understand how we can enmesh human economic activities safely into the environment – and then do so.

Table 18.1 Types of environmental impacts that an LCA may examine and examples

Type of effect[a]	**Example of pollutant, which can cause the effect**
Global warming	Greenhouse gas such as carbon dioxide
Acidification	Acid substance such as sulfuric acid
Eutrophication	Nutrient such as nitrate
Photochemical smog	Hydrocarbons
Terrestrial toxicity[b]	Pesticide
Human health	Chemical such as arsenic
Other types of effect	**Explanation**
Resource depletion	Quantity of resource used compared with how much remains
Land use	Quantity of waste disposed into a landfill

[a] Consideration is also given to whether the impact is local, regional or global (See Table 2.2).
[b] Toxicity to plants and animals of all types.

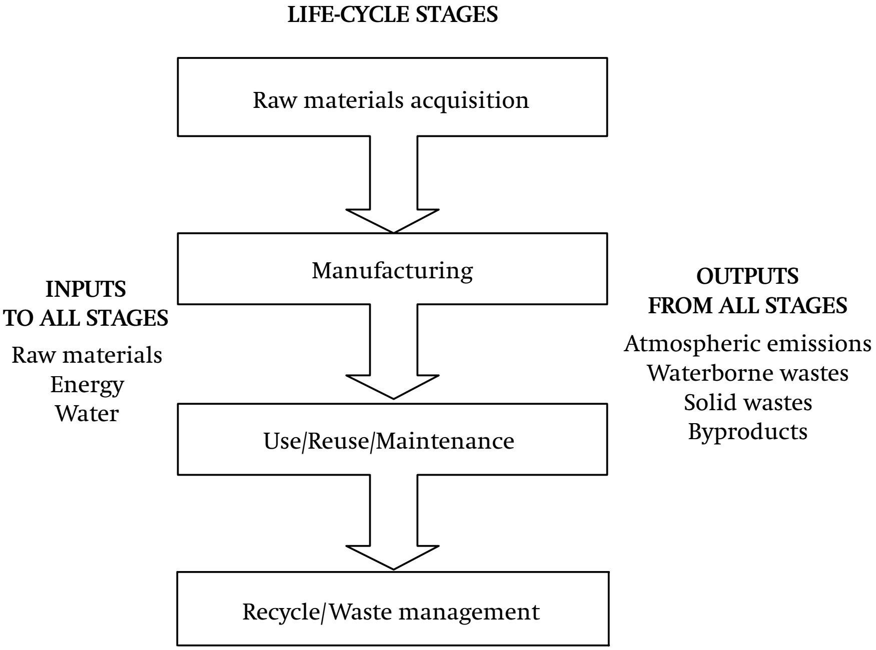

Figure 18.3 What goes into a product's life-cycle assessment? Source: US EPA. 2002. (http://www.epa.gov/ORD/NRMRL/lcaccess/whylca.htm)

- Impacts: What is the impact of each output (Table 18.1)?
- Impact of transportation at each step.

LCA is a complex process

Complicating the situation further is that most products contain more than one component, that is, we must do an LCA for each. Consider the disposable diaper. It contains a plastic covering, a super-absorbent polymer, and paper. As you see, an LCA is not for the faint-hearted. It is an ambitious undertaking, time consuming and expensive. Moreover, as you think about the environmental impacts of a product, remember comparative risk assessment (Chapter 2): the information we seek may not be available or there is information, but what it means may be ambiguous. The same is true when looking at impacts when we do an LCA. Nonetheless, many years have already gone into developing LCA as a tool. More years are going into finding ways to simplify it while still providing realistic results.

Using LCA to make comparisons

LCA can be used to compare two products that serve the same function. Which has the smaller environmental impact, a disposable polystyrene cup or a paper cup? A cloth diaper or a disposable diaper? A truck using diesel fuel or one using propane-gas fuel? Product comparisons are interesting and useful, but there are always uncertainties (Box 18.2). One product may use recycled materials, but otherwise generate more pollution during manufacture or use. One product needs less energy to manufacture but requires more toxic chemicals. Another may be manufactured with little pollution, but present major problems at the end of its useful life. You could make a long list of such difficult to compare factors. Nonetheless, when used with consciousness of its limitations, LCA is useful for product comparison. The US EPA has used it to help develop guidelines for *environmentally preferable products* (Box 11.2).

Box 18.2 | LCA comparisons

Are disposable paper cups better than plastic cups?

Comparing the two items using LCA indicated that a plastic disposable cup is probably no worse than a paper one. However, some believe that a better question would be, which is environmentally preferable, a disposable cup or a reusable one? One is tempted to respond that obviously a reusable cup is preferable. However, an LCA concluded that a glass cup must be used hundreds of times before it is preferable to a disposable cup. The glass cup takes more resources and energy, generates more pollution during its manufacture and transport to market, and each time it is washed uses more energy and water and creates polluted wastewater. Furthermore, a prosperous householder usually has many glass cups. If the householder owned only a few cups, each reused a great many times and washed only when the dishwasher was full etc., glass cups would probably be preferable. The real problem appears to be that prosperous households use many glass cups *and* many disposable cups too.

Are cloth diapers preferable to disposable diapers?

This raises similar issues to those arising for throwaway versus reusable cups. Each time that cloth diapers are laundered, water is used, energy is needed to heat the water, contaminated wastewater is generated, and, unless diapers are hung on a clothesline to dry, energy is used to dry them. If a diaper service is used, transportation to and from the laundry adds to the energy used and pollution produced. On the other hand, disposable diapers create more waste than cloth diapers. This waste is difficult to recycle, although a few cities do so, and if disposable diapers are burned in a waste-to-energy incinerator, some energy is recovered. As you see, it is difficult to compare even simple products. It is a much more ambitious undertaking still to compare complicated products with many components and materials.

Using LCA on one product at a time

■ Volvo preformed an LCA on its vehicles using the results to design more environmentally sound vehicles (Box 11.4). ■ Industry increasingly uses LCA to examine the environmental impacts of its products, often with the goal of reducing those impacts. ■ Sometimes LCA is used for only one aspect of a product as when Proctor & Gamble analyzed energy consumption over the life cycle of its laundry detergents. It found the most energy-intensive step was heating washing-machine water. It then designed detergents that work well in cold water or when less water is used. ■ Generally, LCA provides information invaluable to those who DfE. The more designers know about a product's environmental impacts at each stage of its life cycle, the better a DfE can be.

Design for the environment

Once we analyze a product's environmental impacts, we then ask: Which impacts can we reduce? Which adverse impacts can we design out of this product? You have seen examples of DfE in this text, such as reducing the amount of lead, mercury, or cadmium used in a product, creating more energy-efficient appliances, and *design for disassembly* (Box 11.4). A designer working with DfE uses it from the moment a new product is conceived, thinking from the very beginning of practical means to lessen its health and environmental impacts (Figure 18.4). Designers strive for a product that – over its entire life cycle – uses the least material, energy, water, and hazardous chemicals. Increasingly, designers also look at how to disassemble their product for reuse and recycling.

Earlier, we saw illustrations such as removing cadmium from disposable batteries or hazardous metals from packaging and newspapers. Such actions are important, but did not involve complete product redesign. ■ Xerox Corporation provides a more comprehensive example of DfE. Xerox has been taking back its copying machines from rental users since the 1960s and reusing them. This practice was significant, especially as compared with other companies of the period. However, DfE was not integral to its approach. But in 1990, Xerox began to use DfE from the moment a new product idea was conceived. Criteria were added to a product's design to produce a longer-lived product, one that was easier to disassemble to recover components for recycling or to remanufacture into new copiers. Also built into product design is *remanufacturing convertibility*; that is,

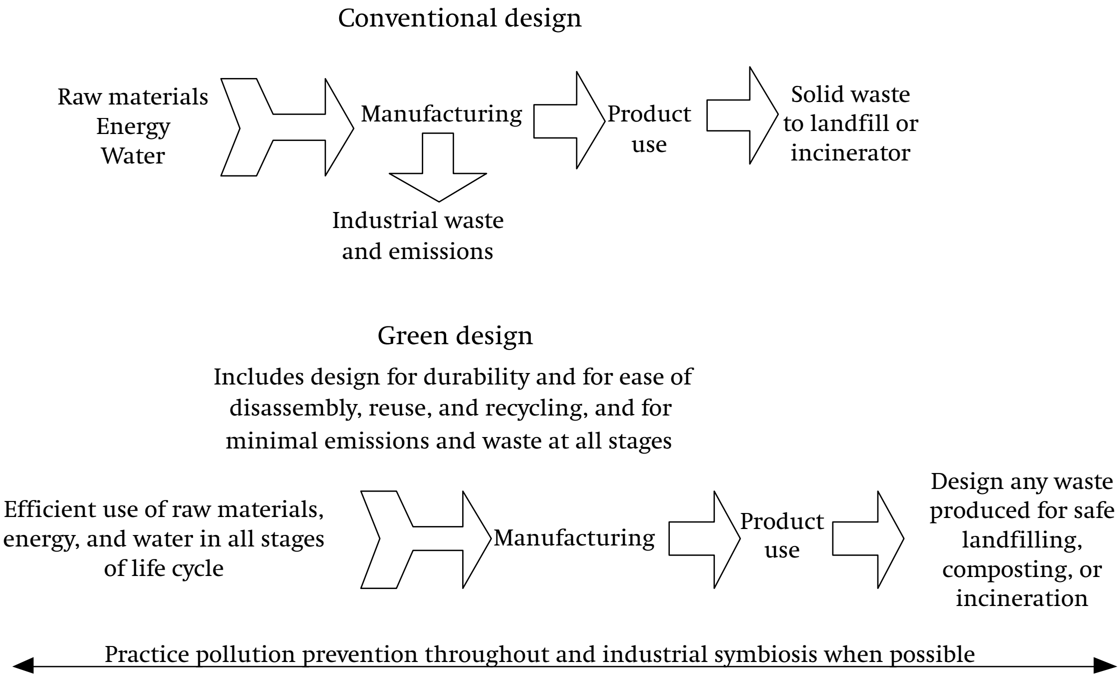

Figure 18.4 Conventional and green product design

product components are designed to allow them to be put to a different use, for example when a photocopier part finds a second life in an electronic printer. Product stewardship is one factor that is driving DfE.

Product stewardship

Product stewardship refers to producers taking responsibility for the products they produce throughout their entire life cycles. Stewardship can be freely chosen by a forward-looking company or, in the European Union stewardship is increasingly imposed through *take-back* laws (or *extended producer responsibility*, EPR). EPR provides a major incentive for manufacturers to redesign their products in a way that they can be reasonably managed at the end of a product's useful life. They ask: Can this product – this car, this computer – be disassembled efficiently? Can the component parts be remanufactured, or recycled? Is the product durable enough to retain value at the end of its useful life? Are components in the product non-toxic, and so easily dealt with at the end of its life?

European take-back laws

■ For simpler products such as packaging, you saw (Chapter 11) that, after EU producers were required to take back packaging, they began to use less packaging. ■ Now, EU manufacturers must also take back their electronics products – not just computers and TVs, but any product containing electronics including refrigerators, stereo equipment, even some toys. In the short term, unless manufacturers are well forewarned, take-back is difficult because products already on the market were not designed for disassembly, reuse, remanufacturing, or recycling. There may be unknowns too even in a producer's own product. These include the purity of potentially recyclable materials, possible unknown hazardous constituents, even the product's material composition. Plastics present special recycling problems (Box 11.3).

EU motor vehicles will shortly be subject to take-back laws too. Manufacturers must reuse or recycle at least 80% of the vehicle by weight. This figure will rise to 85% by 2015. In the United States, Ford has designed a car for Europe's program although there is no such program in the United States ■ European electronics and automobile take-back laws have already greatly stimulated DfE even in the United States. However, in the United States itself, all product take-back is voluntary. Nonetheless, some proactive US companies are working on pilot take-back programs, e.g., IBM has begun an electronics products recycling effort.

Barriers to product stewardship

Producers often resist product stewardship. One reason is that disposal costs are often less than recycling costs. Some virgin industries also receive government subsidies. Remaking a product to the same specifications as the virgin-material product may be difficult or cost more. EPR means producers must develop knowledge of their products' life cycles, which can be costly and time consuming. Product stewardship proponents believe these obstacles can be overcome through education and perseverance.

Buying environmentally preferable products

One powerful means to promote, to *drive* product stewardship is when purchasers who buy large volumes of products – federal, state, and local agencies, universities and colleges – choose to buy products designated as environmentally preferable (Chapter 11). Such large purchasers can drive producers to make environmentally preferable products.

Servicizing

Servicizing means the consumer buys *service,* not the physical product. How can this lead to dematerialization? ■ Recall that Xerox Corporation has leased products for many years, stimulating it to design products that retain usefulness when reclaimed. Xerox has a *Xero-Waste* Initiative, and in 1998 had an 88% recycling rate worldwide. ■ Interface Corp. uses an Evergreen Lease for some business carpets. It leases its carpets to businesses, and lays them down as tiles. In heavily used places, tiles wear out fairly quickly. A representative comes, and removes and replaces only those tiles that need replacing, not the whole carpet.

Servicizing stimulates producers to make durable products because durability is related to profitability. It's an advantage to Interface Corp. that its products are durable. A business using servicizing has an incentive to do more with less: less material, less energy, and less water. Servicizing stimulates LCA too because in order to redesign products producers need to know as much about their life cycles as possible. As one author noted, "information is the lubricant of the transition to a service economy."

Servicizing chemicals

As with other products, the value of chemicals lies in the functions they perform such as cleaning, coating, or lubricating. ■ Consider paint. If you are a producer selling paint by the gallon, you want to sell as many gallons as possible. But what if a car manufacturer hires you to paint its cars? What the manufacturer wants is not quantity of paint, but a quality paint job. This frees the paint producer to ask, how can I increase the efficiency of paint application? In one case (that did not involve outside painters), a Raytheon facility analyzed its operations and found ways to increase its paint application efficiency and, at the same time reduce paint waste by 71%. ■ Navistar produces truck engines. Another company, Castrol Chemical sells Navistar all its coolants, cleaners, and additives. Since 1987, the two companies working together reduced coolant use by 50% and coolant waste by 90%. ■ Other companies such as Motorola are also beginning to bring in chemical managers to help improve the efficiency of chemical use.

The value of these tools

Laws are useful for pollution control, mandating limits on pollutant emissions during production, reuse, recycling, and disposal. Extended Producer Responsibility and servicizing go beyond control. They lead to greater efficiency in the use of materials and energy. EPR and servicizing stimulate producers to use LCA and DfE: when they retain custody of their products, they need to look at their products in a totally new way, from "cradle to cradle."

Box 18.3 | One government intervention

Dealing with the plastic, polyvinyl chloride (PVC) at the end of its useful life is a problem. If landfilled, it does not degrade. If incinerated, hydrochloric acid and other pollutants are produced. Japan developed a PVC recycling system. Construction waste is carefully collected, sorted, and PVC waste is recycled into new PVC pipes and window frames. However, recycled PVC costs more than virgin PVC. To overcome this cost difference, the Japanese government subsidizes PVC recycling, obtaining the funding to do so by imposing a tax on construction sites. The result is a market price for recycled PVC window frames similar to virgin PVC. To further boost sales, the government encourages the construction industry to choose recycled window frames. Government actions have thus led to a transition from using virgin PVC to using recycled PVC.

SECTION IV

Dematerialization and detoxification

Above, we discussed *dematerialization*; that is, reducing material use. However, many industrial chemicals have another problem – many can be toxic or they have properties that accentuate toxicity such as persistence or being bioaccumulative (Chapters 14 and 15). For these substances we need to practice *detoxification*, reducing the use of toxic substances.

Green chemistry: designing chemicals and plastics for the environment

Green chemistry is DfE applied to chemicals. “Green chemistry aims to design the hazards out of chemical products and processes.” To do this the following changes are considered:

1. Change the chemical product. Find or design an alternative chemical that performs the same function as the more dangerous substance, but is more environmentally benign.
2. Change the process. Make a chemical or material using a more environmentally benign process.
3. Other changes are important too. For example producing less waste.

A process is a series of steps or operations used in manufacturing a substance or product. ■ Careful changes in a process can also result in more efficient operations that produce less or no waste; i.e., dematerialization too. Japan, Italy, the United Kingdom, China, Australia, and the United States are among the countries pursuing both research and applications of green chemistry, working toward alternative chemicals and alternative ways to synthesize them. Some examples follow.

Change the product

The global market for the polymer, *polyacrylate* is about 1 million tons (0.91 million tonnes) a year, very large indeed. Polyacrylates are used in industry and agriculture. They are also used in consumer products – a polyacrylate is for instance the super-absorbent component of disposable diapers. They are inexpensive and easy to manufacture. Unfortunately, they “last virtually forever.” Some years ago, chemists at Donlar and Bayer Corporations noticed that a natural biopolymer, *polyaspartic acid*, is chemically similar to polyacrylate. Shellfish produce polyaspartic acid to mold their calcium-carbonate shells. It is biodegradable, and moreover, can be synthesized from a non-hazardous chemical, aspartic acid (an amino acid). Markets are potentially huge, but polyaspartic acid is still more expensive than polyacrylate. Nonetheless, the two companies are persevering in their production of polyaspartic acid. ■ A small example of green chemistry is a technology for decorating glass bottles. The company RevTech Inc. of New Jersey previously made bottle labels with inks containing hazardous metals, cadmium, and chromium(VI); then it developed methods to make colorful inks that are organic and biodegradable. Moreover, less energy is needed to affix the colors to the labels, and the bottles are refillable or recyclable.

Change the process to reduce risk
Illustrations of process change follow.

1. US residents spend about $1.5 billion a year on termite control. This typically involves surrounding their homes with a chemical barrier. The Sentricon system works differently. Monitoring stations detecting termite activity are set up around the home. When termites are detected, bait containing *hexaflumuron* is loaded into the station. This chemical prevents termites from making chitin, an essential part of their exoskeleton; they cannot molt and they die. Hexaflumuron is toxic, but is a "reduced-risk" pesticide because it is not used until termite activity is detected, and then only inside the stations. This method is expected to replace traditional termite treatment.
2. There are ways to reduce the risks of even an extremely hazardous chemical: manufacture it only at the rate that it is used so that it never accumulates. An instance is chlorine dioxide. This is a very useful, but extremely hazardous, chemical. Processes were developed to make it on site and only as needed.
3. Looking into the future, it is possible that miniature chemical plants may be developed that reduce risk. Designers anticipate making chemicals at the site that needs them, and using tiny microchip-based chemical reactors – there would be no need for shipping or storing of hazardous chemicals. Reactors could be installed wherever needed. If an accident or worker exposure did occur, it would be very small. Remember methylisocyanate (MIC), the extremely hazardous chemical used to produce insecticides. It killed thousands in the Bhopal, India accident. MIC remains in use, but can now be made from a much less hazardous chemical. If MIC continues to be used in the future, producing it in a miniature reactor and only at the rate needed would be attractive.

Reducing waste
Synthesizing complex chemicals, such as some pharmaceuticals, sometimes involves many steps. Each step in the process generates some, often much, waste. Thus, "the greenest course of action is to minimize the number of reactions." ■ Zoloft is a well-known prescription drug. It previously took three steps to synthesize sertaline, Zoloft's active ingredient. A procedure was developed that needed only one step. So, whereas previously it took 227 000 l (60 000 gallons) of solvent per ton to synthesize sertaline, it now takes only 6000. The new process eliminated 440 tonnes of titanium dioxide-methylamine

hydrochloride salt waste, 150 tonnes of 35% hydrochloric acid waste, and 100 tonnes of 50% sodium hydroxide waste. All these resulted from changing the synthesis of only one pharmaceutical.

Major changes in how chemicals are made

Using green chemistry signals a major change in perspective in how chemicals are made, but these changes are made only on one or at most a few chemicals at a time. Other green chemists are more ambitious: they want to "introduce radical new technologies that will transform the nature of chemical use and manufacture." A futuristic approach to do this was mentioned above, i.e., developing miniature chemical plants. Other approaches are to use natural systems, *living organisms or the enzymes that they produce*. Some chemical syntheses are already done using organisms or enzymes, but these are limited. Thoughtful chemists want to be able to synthesize many chemicals and materials. Moreover, it is envisioned that biomass would be used too – preferably waste biomass.

Using natural systems – microbes

You have seen how useful microorganisms can be in degrading the organic materials in wastewater, in landfills, and in some hazardous wastes. However, the talents of microbes can be used to make specific chemicals using *fermentation*. Microbial fermentations are already used to make some pharmaceuticals and a limited number of other chemicals. Fermentations with which you are familiar include those for making alcohol and vinegar. Compare the manufacturing of chemicals from petroleum as compared with microbial fermentations: ■ Petroleum. Chemicals manufactured from petroleum typically require high temperature and pressure. They also often require hazardous metal catalysts and hazardous chemicals, and hazardous waste is often produced. ■ Microorganisms. Microbial fermentations work at, or near, room temperature and ambient pressure. The catalysts that they use are enzymes, which they synthesize themselves. In addition, microbes do not need (cannot usually tolerate) hazardous metals or hazardous chemicals, and microbial waste is biodegradable.

One major obstacle to using microbes to make chemicals is that microbes make chemicals that they themselves need. Except incidentally, for example when a mold synthesizes an antibiotic, they don't make the chemicals that we want. However, in some cases we can manipulate microbes using special growing conditions or feedstocks to induce them to make larger amounts of the chemicals we desire. ■ Another way to induce microbes to synthesize specific chemicals is *bioengineering* (genetic modification). This technique introduces new genes into a microbe that lead it to synthesize a specific chemical(s). Example. Billions of lbs of *adipic acid* are produced each year as a feedstock to manufacture nylon and other valuable chemicals. Benzene and toluene have historically been used to make adipic acid. But benzene and toluene come from petroleum, can be risky to use, contribute to air pollution if emitted to air, and produce hazardous waste. Recently, researchers genetically modified common *Escherichia coli* bacteria to get them to synthesize adipic acid from the nontoxic sugar, glucose. The glucose comes from cornstarch, but research is ongoing to obtain glucose from agricultural wastes such as corn stalks. In the future, the *E. coli* process may be a valuable means of producing adipic acid and other useful chemicals.

Using natural systems – enzymes

Enzymes are proteins that all living organisms make to carry out necessary metabolic reactions. Thousands of different enzymes exist. Each catalyzes one or a limited number of reactions. Individual enzymes can be purified from microorganisms, plants and animals. An isolated enzyme catalyzes specific reaction(s) to produce the specific chemicals dictated by that enzyme. This differs from microbial fermentations where the desired chemical is but one of many chemicals made. Again, because enzymes are selective, there are fewer unwanted byproducts. Other positive attributes are that like the living organisms from which they are derived, enzymes do not use (cannot tolerate) toxic chemicals, hazardous metal catalysts, or high temperature. Some do require a metal to do their work, but the metals they use are nutrients such as iron. ■ Sometimes enzymes make polymers, which may be of economic importance; In addition, such polymers are biodegradable. ■ There is much hope that enzymes will begin to replace petroleum in the synthesis of many chemicals.

Using agricultural and other biological byproducts

As just noted, it would be extremely attractive if the new process for making adipic acid could use waste organic material as the source of glucose, not starch. There are many organic wastes, including agricultural wastes (corn stalks, rice straw, etc.), waste paper, cheese whey, and industrial sludge from biological processes. There is even hope that – eventually – manure and sewage sludge could become chemical feedstock.[8] An agricultural waste, perhaps after treatment with lime to make it more biologically available may be "fed" to microbes that are similar to those found in the stomachs of cattle. These would ferment the waste into chemicals such as acetic, propionic, and butyric acids. One author stated: "If there is a modern-day version of alchemy, it is probably the conversion of agricultural and municipal waste into ethanol." Nonetheless, BC International has started doing just that. It built a large plant to make ethanol and other chemicals from

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[8] Manure is already used to generate methane in usable amounts. A prison in Washington State (United States) generates its own electricity using methane as a fuel. The methane is produced by allowing anaerobic microbes to ferment manure in a closed digester. The manure comes from farm animals maintained on site. Some dairies in Oregon State also produce methane from dairy manure; some households in very-poor countries generate methane from manure and then use the methane for fuel in their homes. But the use of manure or sewage envisioned in this chapter goes further. They are seen as feedstocks useful in the synthesis of a variety of chemicals.

agricultural wastes such as straw, waste sugar cane, and stover (dried stalks and leaves of cereal crops), and forestry wastes such as tree branches. BC has only recently started up so it is too soon to know whether it will be profitable. Another attractive feature of waste materials is their "negative cost." Because one ordinarily pays to dispose of waste, it may be possible to obtain the waste for the cost of transport.

Using biochemicals and biopolymers is not a free lunch
All microbial fermentations or enzymes would produce waste, much waste such as great masses of microbe bodies. These are biowastes, so can be composted or used as fertilizer. However, whenever very large amounts of waste are produced, dealing with them can be difficult.

Another reason for considering biomass an attractive source of chemicals and polymers is because biomass is renewable. This is very appealing. Corn is pushed as a source of ethanol to add to gasoline (as an oxygenated chemical to promote cleaner burning) or as a source of glucose to make biodegradable biopolymers. But the net environmental effect may not be positive. Much energy is needed to grow corn. Much fertilizer and pesticides are needed too, which run off into water along with eroded soil. Indeed, there are major concerns that for some of our common crops, of which corn is a major example, soil is being mined rather than farmed sustainably. Another question that needs addressing is should the land be used for growing food rather than to grow biomass to make chemicals? Or, should it be left to wildlife increasingly pushed to extinction because humans are destroying their habitats? ■ Recently, Dow Chemical and Cargill Inc. built a large facility to use corn as a source of glucose to make the biodegradable polymer *polylactide*. Polylactide can be used in clothing, carpet, diapers, packaging, and other products. For the reasons just noted, corn itself may not be attractive. However, in the future it may be possible to use wheat, rice, and – most importantly – agricultural waste as a glucose source. Using waste would probably make the process more attractive environmentally.

Box 18.4 | Environmentally benign manufacturing (EBM)

EBM addresses the question of "how to achieve economic growth while protecting the environment." Indeed, the first sentence in a report from a panel that examined EBM is, "Is '*environmentally benign manufacturing*' an oxymoron?" The EBM panel was sponsored by the US National Science Foundation and the Department of Energy. It examined manufacturing sectors making plastics, electronics, automobiles, and metal products. Most US industrial waste results from manufacturing (Figure 18.1). However, the thinking of panel members encompassed all life-cycle stages of a product (Figure 18.3) not just manufacturing. EBM is sometimes called smart production or lean production. Counted among its tools are LCA and DfE. Striving for absolutely minimal waste is considered lean production by progressive companies. The EBM panel found one Toyota assembly plant in Japan that produced only 18 kg of landfill waste per vehicle produced.

EBM focuses on technologies that can ameliorate manufacturing's environmental impact. The EBM panel, chaired by Dr Timothy Gutowski of the Massachusetts Institute of Technology, visited many sites in the European Union, Japan, and the United States that make metal products, polymers, automobiles, and electronics. The panel report pointed out the environmental problems of each sector, from raw materials extraction to manufacturing, product use, and recycling. It identified technologies that would be needed if EBM were to become a reality. The panel compared Japan, Europe, and the United States; looking at national EBM strategies, how the roles of government and industry differed among countries, and how research and development efforts differed. An encouraging finding was that manufacturers, especially international firms, showed "a clear trend towards 'internalization' of environmental concerns." Moreover, the same companies that successfully pursued EBM were also able to integrate "technology, economic motivation, regulatory actions, and business practices." The panel came away convinced that many companies do understand that their long-term success is based on a sustainable environment (see http://www.wtec.org/loyola/ebm/ebm.pdf and Internet resources).

Recycling carpet "forever"

Nylon is a plastic that is very difficult to recycle. So the development of closed-loop recycling for nylon carpet is a special success. The US alone uses about 1.4 billion lbs (635 million kg) of new nylon carpet each year. It landfills old carpets where, because they don't biodegrade, they persist indefinitely. Nylon is not a *thermoplastic*; that is, it cannot be melted down like the plastic in a soda bottle. To recycle nylon, it must be depolymerized, broken down into the subunit chemicals from which it was made. Then the subunits must be purified to meet the same standards as chemicals made from virgin resources. Only then can new carpet of quality equivalent to virgin ones be made. In some cases the backing must be stripped off too, not an easy task. Nonetheless, Dupont, Evergreen, and BASF Corporations have built nylon-carpet recycling facilities in North America and Europe. They intend to make their facilities cost competitive with those making virgin carpets.

Their effort represents great progress – but it is not a completely closed loop. The processes of depolymerization, purification, and remanufacturing do produce waste. Glues and other extraneous matter are associated with old carpets; carpet backing must be dealt with too. In addition, collecting carpets isn't easy. Some local recyclers obtain used carpets directly from commercial establishments that rip them out. Dupont and other companies have begun asking municipalities to do curbside carpet collections. This is more difficult. Dupont and Evergreen recycle only nylon carpets – but there are many other types of carpets too, other synthetics, wool, and cotton. An association of European carpet makers collects all kinds of carpets for recycling. In the past they sorted the various carpet types by hand using a scanning device, but now have an automated sorting system. They expect to process 55 million lbs (25 million kg) of carpet each year. This may seem like a great deal, but remember that the United States alone landfills several billion lbs of carpet each year. But any effort must have a beginning.

SECTION V

Progress toward zero waste

Businesses committing to zero waste and sustainability

Some facilities have greatly reduced their solid-waste generation even without making a zero-waste commitment. Examples mentioned earlier in this text were an International Paper Company pulp and paper mill that reduced its solid waste 91% between 1988 and 2001 (Figure 2.3), and a Toyota assembly plant in Japan that produces only 18 kg of landfill waste per vehicle produced (Box 18.4). Another example is Epson, an Oregon computer-printer maker that recycles 90% of its materials and incinerates the rest for energy.

Some companies have deliberately committed themselves to zero waste. ■ Xerox's Xero-Waste program has been noted. Pillsbury (Minnesota) now diverts 96% of its waste to productive purposes and is working toward 100%. ■ Fetzer Vineyards in California cut its garbage generation 93% and is aiming for zero by 2009. It cut wastes by composting large quantities of grape seeds and corks, committing to buying recycled products, and using recyclable packaging for all its products. It also developed enough solar capacity to power its own buildings, and to fill and cap 1.2 million bottles of wine each year. Fetzer also converted its vineyards to organic agriculture, which eliminated pesticide emissions.

To be "sustainable" means even more than going to zero waste. To be sustainable, a company must rethink all stages of the life cycle for each of its products. Interface is a proactive carpet company, vigorously pursuing the goal of sustainability. To Interface this means, "to take nothing from the Earth that is not renewable and do no harm to the biosphere." One of Interface's programs, Evergreen Lease, was noted above.[9] ■ Other companies too are striving to varying extents to pursue principles of sustainable development.

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[9] On its web page, Sustainability Overview (http://www.interfaceinc.com/goals/sustainability_overview.html), Interface Corp. states: "We believe that there's a cure for resource waste that is profitable, creative, and practical. We must create a company that addresses the needs of society and the environment by developing a system of industrial production that decreases our costs and dramatically reduces the burdens placed upon living systems. This also makes precious resources available for the billions of people who need more. What we call the next industrial revolution is a momentous shift in how we see the world, how we operate within it, what systems will prevail and which will not." "Our vision is to lead the way to the next industrial revolution by becoming the first sustainable corporation, and eventually a restorative enterprise."

Cities committing to zero waste

- Canberra, Australia (population 312 000) has formally adopted zero waste as a city goal. To demonstrate its commitment, Canberra is working to eliminate its two landfills by 2010 and replace them with "resource recovery estates." These estates have a processing plant to separate materials and reprocess useful materials, and have created 70 jobs. Canberra believes. "The potential for further job creation is only limited by effort and imagination." It intends to co-locate recycling industries with industries that treat "wastes" as resources, the outputs of one process will become inputs to other businesses; that is, it will pursue industrial symbiosis (Figure 2.2). Canberra also aims to become a model of excellence for other cities and to foster eco-tourism.
- Seattle's population is about ten-times greater than Canberra's. In the late 1990s Seattle became discouraged because, despite much effort, its recycling rate was only about 40%. In 1998 it adopted a different approach deciding to use zero waste – if not as an absolute goal – as a guiding principle. "This principle entails managing resources instead of waste," "conserving natural resources through waste prevention and recycling; turning discarded resources into jobs and new products instead of trash; promoting products and materials that are durable; and discouraging products and materials that can only become trash after their use."
- Analogous to Canberra, some US cities have created resource recovery parks: the city creates a central location for recycling, composting, and reuse facilities. New manufacturing and retailing facilities co-locate in the parks to use incoming materials. A Berkeley, California project, *Urban Ore*, has departments that sell recovered materials to the public – building materials, hardware, arts and crafts materials, media equipment, etc. Urban Ore aims to add businesses to rebuild and upgrade old computers, and make unusual items from scrap metals and from recycled glass.

Other ways to reduce municipal solid waste

- *Composting* is an important means of reducing organic wastes, a means not yet fully exploited. Many communities compost leaves and yard waste, but leave large amounts of other compostable materials in their municipal solid waste (MSW) stream. Systematic composting could help communities move toward a zero-waste goal. About 15% of US MSW is food. Perhaps twice that much is unrecyclable paper such as fast-food wrappers contaminated with fryer oil. Such organic material can be composted. More households could learn to compost, or these biomaterials could be separated out so that communities could compost them.
- "*Pay as you throw*" is another significant way to reduce MSW. Householders pay for each bag of trash that the municipality collects from them. Seattle, Washington, and San Jose, California reduced waste as much as 65% when they added both composting and pay-as-you-throw to their recycling programs.

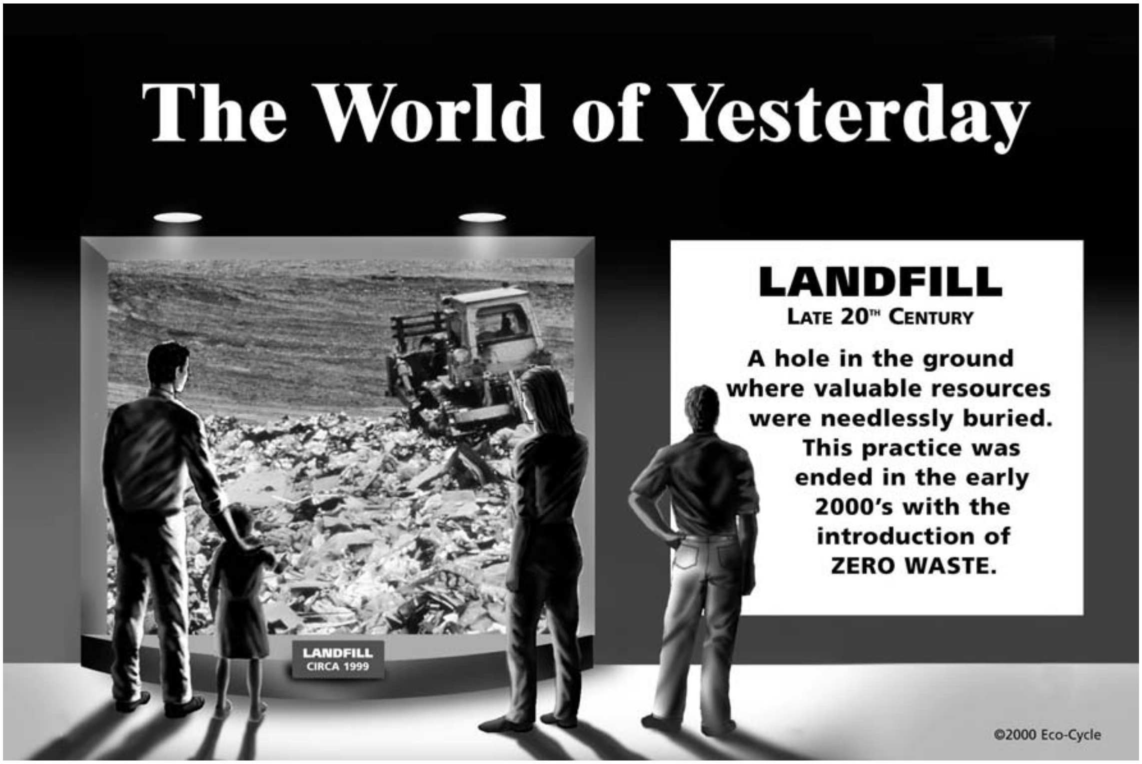

Figure 18.5 Thinking of a landfill in the past tense. Credit: Eco-cycle (www.ecocycle.org)

Countries committing to zero waste

New Zealand began a zero-waste effort in 1999 (Figure 18.5 and Box 18.5). They envision zero waste as, "an efficient human economy that exists within the limits of nature." ■ More than one-quarter of New Zealand's local authorities embraced this program. Many committed themselves to zero waste by 2015. Each committed locality received a NZ$25 000 grant. Each carries out research on what recycling and waste-reduction approaches would work best in its community to reduce landfilling, conserve resources, and create jobs. ■ Businesses also are participating: by the end of 2000, six Auckland stores had already reached zero-waste status – they no longer have dumpsters. Another country, Canada started a similar campaign, Target Zero Canada, on Earth Day 2000 (http://www.targetzerocanada.org/).

Box 18.5 | A New Zealand vision

"The end of waste: zero waste by 2020" is a challenge that New Zealand's government issued to its citizens in 1999. Move from waste management to waste elimination. "All around the world a consensus is emerging that in the end there is only one safe way to deal with waste, and that is to eliminate it. This is our personal invitation to all New Zealanders to support the adoption of a national zero waste vision: a vision that will create employment and wealth and protect precious resources for future generations." New Zealand's vision applies three core principles.

- 1. End cheap waste disposal. Cheap disposal has helped create a hugely inefficient industrial system that externalizes costs to the environment and future generations.
- 2. Design waste out of the system. Incorporate technologies to reduce waste at all points along the supply chain. Emphasize DfE: "The best way to eliminate waste is to design it out from the beginning. We need to create an environment whereby anyone designing a product will first think about the need for that product, and second, how to ensure that no waste is created in it's production, use, and final return to the human economy or nature."
- 3. Engage the nation. "We need to engage each and every person at a national and community level in our quest for Zero Waste. We must . . . unleash the creativity and energy of communities, businesses and institutions in the pursuit of Zero Waste." (See http://www.zerowaste.co.nz and Internet resources.)

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Some think the world's problems are too overwhelming to address. Others believe that "mega-problems" have solutions too. Architect Jaime Lerner, former mayor of Curitiba, Brazil stated, "There is a kind of syndrome of tragedy that poisons our thinking . . . The problems are so great, people say no solution is possible. That's the mentality of defeat, and an excuse for doing nothing. The fundamental thing is to begin."

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Index