Chapter 15

Waste Processing and Detoxification

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Main Messages

Ecosystem processes may act to reduce concentrations of substances that are directly or indirectly harmful to humans. This capacity is finite, has been exceeded locally in many places, and is exceeded across some whole regions. The cases of stratospheric ozone depletion by chlorofluorocarbons and climate change due to greenhouse gas buildup demonstrate that the capacity to alter the environment in harmful ways through by-products of human activities has now reached global proportions.

Humankind produces a large variety of wastes that are introduced into the environment either by accident or by design. Wastes are by-products of human activity and include human excrement wastes, agricultural wastes, energy and manufacturing wastes, industrial and consumer chemical products, medical and veterinary products, and transportation emissions.

All cases of wastewater-borne disease, human health impairment due to contaminants, environmental degradation due to waste discharges, and contaminant-caused impacts on biota are failures in waste management. The management of wastes is an important function of human societies and essential to the promotion of human well-being. The mismanagement, or neglect of management, for any of the many waste types leads to impairment of human health, to economic losses, to aesthetic value loss, and to damages to ecosystems, biodiversity, and ecosystem function.

Deferring waste management actions until the problems become large is not an effective management approach. The costs of trying to reverse damages to waste-degraded ecosystems or remove toxins from the environment, if possible at all, can be extremely large and burdensome on society.

The capacity of an environment to adsorb wastes without damage to human well-being or to ecosystems depends on the ecosystems' ability to detoxify, process, or sequester (that is, isolate from the biosphere) waste contaminants. The no-damage limit or capacity for assimilation is highly variable. This variability is a result of the properties of different contaminants and the differing characteristics of specific ecosystems. Loading limits also depend on human judgments as to what is an acceptable level of human health risk or alteration of an ecosystem.

The levels of a waste chemical that are harmful to the ecosystem may be either much higher or much lower than for human health. For example, by the time human health effects are noticed, there may already have been substantial changes in the ecosystem and vice versa. Further, the sensitivity of different organisms within ecosystems may be very different for a particular contaminant. Different waste contaminants may have local, regional, or global impacts.

Some waste contaminants (such as metals and salts) cannot be converted to harmless materials and will remain in the environment permanently. With continued introduction into an environment, the concentrations of such contaminants will continue to increase. Many other contaminants (such as organic chemicals and pathogens) can be degraded to harmless components. And depending on the properties of the contaminant and its locations in the environment, degradation can occur at relatively fast or extremely slow rates. The more slowly a contaminant is detoxified (that is, the more persistent it is), the greater the possibility that harmful concentrations of the contaminant will be reached in the environment either locally or globally.

Some wastes, such as nutrients and organic matter, are normal components of natural ecosystem processes but can reach harmful levels due to human activities. Inputs of these materials may sufficiently exceed natural rates so that ecosystem functions are modified or impaired. Nutrients and organic matter, when applied at appropriate rates and locations, are an important resource for the improvement of agricultural soils.

The fate and effects of chemicals introduced into the environment can be predicted (in most cases with useful accuracy), so as to allow informed waste management decisions to be made. Due to the great number of possible contaminants, as well as the continuous generation of new compounds, and to the complex interactions within ecosystems, our understanding of the consequences of some contaminants is incomplete.

The problems associated with wastes and contaminants are in general growing worldwide. Some wastes are produced in nearly direct proportion to population size, such as sewage wastes. Other wastes and contaminants reflect the affluence of society. An affluent society uses and generates a larger volume of waste-producing materials such as domestic trash and home-use chemicals. Where there is significant economic development, loadings of certain wastes are expected to increase faster than population growth. The generation of some wastes, such as industrial ones, does not necessarily increase with population or development state. These wastes may often be reduced through regulation aimed at encouraging producers to clean discharges or to seek alternate manufacturing processes.

It is not possible at this stage to state whether the intrinsic waste detoxification capability of Earth will increase or decrease with a changing environment. The detoxification capabilities of individual locations change with changing conditions. However, it is certain that at high waste-loading rates, the intrinsic capability of ecosystems can be overwhelmed such that wastes build up in the environment to the detriment of human well-being and the loss of ecosystem biodiversity and functions.

15.1 Introduction

This chapter addresses two major topics: the general characteristics and patterns of waste production and the capacity of ecosystems to detoxify or otherwise adsorb human-produced wastes. The first is addressed by showing some trends in major categories of wastes, attempting to indicate in particular the relationships between population and level of development and waste production. The second topic is complex due to the wide variety of types of wastes produced by human activities and to the complex set of ecosystem processes that determine the fate and effects of wastes in various ecosystems. The chapter shows how ecosystem processing of wastes and waste loadings interact to determine the damages of particular wastes.

The term "wastes" in this chapter refers to materials for which there is no immediate use and that may be discharged into the environment. It includes materials that might otherwise be useful if they were not in the environment, such as oil after an oil spill or pesticides once they are no longer at their site of application. The term "pollutant" is not generally used here. A waste in the environment is a contaminant but not necessarily a pollutant in the sense of loss of use of ecosystem services.

Although there is no attempt here to systematically assemble and estimate the damage to humans and ecosystems done by past waste releases, a few examples of the types, issues involved, and magnitude of damages of wastes that exceeded ecosystems' capacity are provided in order to illustrate the importance of managing wastes.

The intent of this chapter is to lay down a foundation for decisions regarding wastes and to establish the importance of waste management for human well-being at both the local and the global scale.

15.1.1 Humanity's Many Types of Wastes

Human activities discharge many types of materials into the environment:

- *Industrial by-products resulting from the production of durable goods, pharmaceuticals, and other manufactured goods* used by society: Some of these materials are novel to natural systems (xenobiotic), which means they did not exist on Earth before being manufactured by humans. Ecosystems may be very ineffective in detoxifying novel chemicals, and so they may be particularly persistent and thus accumulate in the environment.
- *Nondegradable wastes, which cannot be broken down to harmless materials*: These can only be diluted. This category includes metals and salt wastes. Typically, salts are not a problem once they reach the ocean, but metals cause problems in any ecosystem.
- *Pesticides*: These may indiscriminately kill even beneficial insects, and persistent pesticides may accumulate in organisms and have harmful effects on other organisms in the food web.
- *Fertilizers,* the most important of which, quantitatively, are nitrogen and phosphorus compounds.
- *Excrement, or sewage wastes,* rich in organic matter and in nitrogen and phosphorus (plant fertilizers or nutrients) and carrying pathogens: The organic matter in sewage can remove oxygen from aquatic systems, and the nutrients may stimulate plant growth and alter ecosystem structure and function.
- *Natural materials,* which are often released at rates that greatly increase environmental concentrations, thereby often harming ecosystems and human health: Included here are toxic metals, salt wastes, acid wastes, reactive nitrogen, carcinogenic polycyclic aromatic hydrocarbons (found in smoke and exhaust), and petroleum products.
- *The by-products of day-to-day human activities*: This category includes materials made from paper, plastics, glass, metals, and products such as household chemicals, and pharmaceuticals, which become wastes after they are used and, in one form or another, end up in the environment.

Table 15.1 provides a more detailed listing of the major categories of wastes introduced into the environment. The individual materials within a category may have different behaviors in the environment and represent very different types and levels of risks. It should be recognized that some of the categories in the table include a great number of different types of materials. For example, the Registry of Toxic Effects of Chemical Substances (MDL 2003) lists over 150,000 chemicals. Another compendium, *The Merck Index* (O'Neill et al. 2003), lists over 10,000 individual biologically active pharmaceuticals, chemicals, and biological compounds. Further, thousands of new compounds are being synthesized and manufactured each year.

Wastes may be classified as either "point source" or "non-point source." Point source wastes are those discharged from a specific facility or at a specific location. Typical of these facilities are industrial operations or sewage processing facilities where the discharge location is readily identifiable, often a single pipe or smokestack. (It should be noted that a sewage treatment plant is not the actual source, but a collecting point for wastes.) The other major category, non-point source wastes, includes urban runoff, acid rain, and agricultural runoff. The distinction between point and non-point sources is somewhat arbitrary, however, as the place in time and space at which a large number of small point sources become non-point source is subjective.

Different types of wastes are also often mixed together, making management of wastes more difficult. For example, the mixing of industrial effluents with domestic sewage impairs possible beneficial uses of waste waters. Domestic sewage, properly treated to kill pathogens, may make suitable fertilizer and soil enhancers for agricultural purposes. However, metals or chemicals often contaminate centrally collected sewage, precluding the use of the sewage for such beneficial purposes. Many household chemicals such as pesticides, pharmaceuticals, and cleaners may also render domestic sewage unsuitable. For example, irrigation with industrial waste waters has been associated with enlarged livers, cancers, and malformation rates in areas in China (Yaun 1993) and with cadmium poisoning in Japan (WHO 1992).

Reuse of domestic waste waters is easier when grey waters (those, for example, from washing) are not mixed with black waters (those containing excrement). The grey waters can be used especially for small-scale irrigation with low risk of disease transmission (Faruqui et al. 2004). If mixed wastes (such as municipal wastes) are incinerated, special technology is required to prevent potentially harmful materials (such as noncombustible metals) from entering the incinerator's air emissions and causing air pollution. The ash of incinerated mixed waste may also have high levels of contaminants, requiring careful disposal.

15.1.2 Types of Damage Caused by Wastes

Wastes can cause harm in many different ways. It is convenient to consider three general different types of harm:

- direct impairment of human health;
- damage to ecosystems or organisms that creates economic losses; and
- damage to organisms in an ecosystem, with loss of biodiversity.

15.1.2.1 Impact of Wastes on Human Health

There are many examples of human health problems associated with wastes:

- Pathogens in sewage wastes transmit diseases. Such pathogens include cholera, typhoid, shigella, and viruses, causing diseases such as diarrhea, polio, meningitis, and hepatitis. It is estimated that 1.8 million children in developing countries (excluding China) died from diarrheal disease in 1998, caused by microorganisms, mostly originating from contaminated food and water (WHO 2003) (some reported food cases may not be from wastes but from direct contamination by other humans and poor hygiene in food preparation). Worldwide, a lack of suitable sanitary waste treatment is estimated to cause 12 million deaths per year (Davidson et al. 1992).
- For metals, the severe health effects of mercury being discharged into the environment were learned in the painful lesson of Minimata Bay Disease (actually not an infectious disease, but mercury poisoning) first identified in the late 1950s, where nearly 3,000 people were stricken with disease or died after mercury was dumped into the environment. Lead is another metal of high concern. Lead has entered the environment as an additive in gasoline and paints. For example, lead exposure in Mexico has resulted in 40–88% of the children in various communities having blood levels of lead higher than exposure guidelines (Romieu et al. 1994, 1995). Lead exposure can reduce growth and cause learning disabilities and neurological problems.
- A number of persistent organic pollutants have become of enough concern to stimulate the generation of international conventions to stop their use (such as the Stockholm Conven-

Table 15.1. Major Categories of Wastes and Contaminants Listed by Source

Category	Types of Wastes	Character of Source	Extent of Impact
Industrial sources			
Energy producers Coal, oil, and gas, production of coking coal Nuclear plants	metals, PAH, fixed nitrogen, waste heat, fly ash, spent fuel, CO_2	point source	local to regional to global
Manufacturing and chemical wastes	wide variety of types; often synthetic chemicals, solvents, and/or metals	point source	local to regional
Mining	metal-contaminated water and soils, acidified water	point source	local to regional
Transportation accidents	oil spills and chemical spills	point source	local to regional
Waste incineration	particulates, PAH, dioxins, fixed nitrogen, phthalates	point source	local to regional
Agricultural sources			
Livestock production systems	pathogens, including species-jumping bacteria/viruses, organics, nutrients, salts; pharmaceuticals, including antibiotics	non-point source	local to regional
Cropping systems	herbicides, fungicides, and insecticides; nonusable plant materials, nitrogen, phosphorus	point and non-point sources	local
Land preparation and rangeland management	PAH, particulates (from set fires)	point and non-point sources	local to regional
Human habitation sources			
Sewage	pathogens, fertilizers, organic matter, residual pharmaceuticals	point and/or non-point sources	local to regional
Heating source emissions	PAH, particulates	non-point source	local to regional
Consumer hazardous materials	cleaners, paints, automotive fluids, pesticides, fertilizers, batteries, cells	point and/or non-point sources	local
Trash	organics, leachates containing nutrients, salts, metals, plastics, glass	point and/or non-point sources	local
Transportation, including shipping, aviation, and automotive sources	PAH, reactive nitrogen, lubricating oils, coolants, lead	non-point source	regional

tion on Persistent Organic Pollutants and the Aarhus Protocol on Persistent Organic Pollutants). For example, the concentrations of polychlorinated biphenyls in fish from certain waters are great enough to warrant official advisories against eating the fish. PCBs have been found in human tissues and human milk throughout the world (Jensen and Slorach 1991).

- It is estimated that air pollution in China causes more than 50,000 premature deaths and 400,000 new cases of chronic bronchitis a year (Harrison and Pearce 2000; UNEP 2000). Air pollution may aggravate asthma, and in the United States approximately 600 children die annually from asthma and 150,000 are hospitalized (CDC 1995). (See also Chapters 13 and 27 for a further assessment of air pollution.)

Humans are exposed to wastes by drinking water containing hazardous substances from waste residues, by ingesting foods with waste residues, by inhaling airborne wastes, or by through-the-skin exposure after physical contact with waste residues. Drinking contaminated water is a common route of exposure for many wastes that are leached into surface or groundwaters. Examples of food exposure routes include agricultural pesticide residues on foods, contamination during food preparation, and bacteria accumulated by edible clams that filter and concentrate particles from water.

Inhalation is a route of exposure for airborne wastes, such as the polycyclic aromatic hydrocarbons in smoke and automotive exhausts, or for pesticides carried downwind of the site of application. Through-the-skin (dermal) exposure is most often associated with worker exposure to materials they are handling, but it is also a route for wastes, such as for residential use pesticides, and for parasites. The dermal and inhalation exposure routes highlight significant overlaps between worker safety issues and waste issues.

15.1.2.2 Economic Losses

Detriment to ecosystems or specific organisms by the introduction of harmful wastes can lead to significant economic losses:

- When a body of water becomes anoxic from eutrophication through excess nutrient inputs, it can no longer support commercial, subsistence, or sport fisheries. Worldwide, there are now at least 146 areas in the coastal environment where low oxygen concentrations occur either chronically, seasonally, or episodically (UNEP 2004).
- A major economic loss has resulted from the use of the antifoulant agent tributyltin used in paints for ship and boat hulls.

Pleasure boats are often kept in high-density moorings and docks in close proximity to where oysters are grown. The species and race used for the oyster aquaculture industry in Europe is about 100 times more sensitive to TBT than are typical aquatic test organisms. As the pleasure boating community adopted TBT-based paints as the hull paints of choice in the 1970s, oyster farming operations throughout Europe experienced huge decreases in yield. For example, in Arcachon Bay, France, annual oyster production dropped from around 13,000 tons to about 3,000 tons between 1977 and 1983. Further, surviving oysters grew deformed, rendering them unsuitable for market. Economic losses for Arcachon Bay over this period were estimated at 800 million francs (Alzieu 1990). Banning the use of TBT paints on small vessels alleviated the immediate threat to the European oyster industry.

- Discharges of wastes into the environment can also cause economic losses even where there may be no clear detriment to the local organisms. For example, in U.S. coastal waters about 15% of potential commercially harvestable shellfish beds are closed due to water quality problems, primarily from sewage discharges (NOAA/ORCM 2003).
- When human health is affected by wastes such that a person is unable to work, there are direct economic consequences.

15.1.2.3 Damage to Ecosystems and Loss of Biodiversity

Wastes present in the environment can harm organisms. Terrestrial organisms may be exposed to wastes through the food chain, through inhalation, or through direct contact. Aquatic organisms may also take up wastes directly from the water.

- Where sufficiently high levels of contamination occur, organisms may receive acutely toxic exposures and die in mass. For example, fish kills have resulted from industrial discharges or runoff of agricultural pesticides (Heileman and Siung-chang 1990). Deaths of aquatic and bird wildlife are often the immediate and visible result of large oil spills, although there may also be long-term residual toxicity resulting from large oil spills (Peterson et al. 2003).
- More subtle and less evident are wastes that change the behavior or the biology of organisms but are not in themselves lethal. A well-known example was the widespread use of DDT and its effects on high-trophic-level birds, which did not die but could not successfully reproduce. Currently, there is concern that other chemicals, such as hormone disrupters, may affect organisms at concentration levels below those causing effects evident in standard toxicity tests. Some of these may disrupt the hormone systems of some organisms, affecting their behavior or reproductive physiology and reducing their capability to survive or reproduce (NTP 2001; deFur et al. 1999).
- Ecosystems can be damaged by changes in their chemical composition. For example, acid rain—a result of sulfur and fixed nitrogen emissions from power plants, motor vehicles, and agriculture—can alter the chemistry of soil. This stresses vegetation and alters the species composition of lakes and streams, sometimes to the point of making the lake unable to support fish life (Driscoll et al. 2001; Galloway 2001).

15.1.2.4 Different Thresholds for Human Health, the Ecosystem, and Economic Loss

The thresholds for effects in the three general types of damage—human health, economic losses, and damage to ecosystems—may be quite different. Acceptable waste concentration limits to protect human health may overwhelm some ecosystems and result in economic losses.

- The effective pesticide DDT has a low acute (short-term) toxicity to humans. From a human perspective, its use was relatively safe and is still used inside households for malaria control, and although there could be significant sublethal human health effects as well, it was primarily DDT's effects on the reproductive capabilities of birds that made its use unacceptable.
- The antifoulant paint ingredient TBT is apparently harmless to mammals (including humans) at environmental concentrations that are lethal to oysters. Although the use of TBT caused economic losses in Europe and harmed some other mollusk populations as well, ingestion of TBT-contaminated organisms was not considered or regulated to address a human health problem.
- The effects of low levels of many carcinogenic chemicals (such as PAH) or ionizing radiation are of great concern for human health where each individual is valued, yet are usually not risks to the health of wildlife populations.

Given the different sensitivity of different species, including humans, to chemical residues, a chemical exposure standard set to reduce human health impacts may not be sufficient to protect wildlife, or vice versa. As such, individual evaluations are required to fully understand the consequences of varying waste concentrations on human health and ecosystems.

15.2 Trends in Waste Production

The amounts of wastes released into the environment in many ways depend on choices made by governments, organizations, and individuals. Trends for some categories of wastes by themselves are not necessarily predictive of future trends, as waste-generating behaviors may change. And the future magnitude of waste problems depends on how wastes are managed in relation to the capacity of ecosystems to detoxify wastes.

In order to understand the actions required for adequate waste management, recognizing the role of ecosystems in waste detoxification, it is useful to examine relationships between waste production and different segments of the human population. The production of some wastes is closely related to population size, while some production is more related to human practices in agriculture and manufacturing, which often correlate with a nation's state of development.

15.2.1 Population-proportional Wastes

The amounts of human excrement wastes (feces and urine) produced are essentially proportional to human population size. Although there may be some differences in the composition and per capita production of excrement depending upon the nutrition status of the population (for example, the nitrogen content of sewage depends on the amount of protein in the diet), the overall variability in composition is relatively small. The total amount of human excrement wastes will increase in proportion to population growth.

The urbanization of populations (see Chapter 27) and the general increase in coastal populations (see Chapter 19) will tend to concentrate the excrement production into relatively limited areas. If damage to ecosystems from the nutrients and organic matter in human sewage is to be prevented, and if sewage-carried pathogens are to be reduced or eliminated, efforts to manage human excrement wastes must increase in proportion to the population size. Where the oxygen demand (mostly due to the decay of carbon compounds in the sewage) and nutrient fertilizers in excrement wastes are not removed from sewage, especially in waste-receiving waters near large urban areas, the loadings to the environment can easily exceed the capacity of ecosystems to adsorb them without causing harm to the environment. Pathogen destruction and the removal of oxygen demand can be managed very effectively by modern sewage treatment. With additional treatments (and often significant expense), the amount of nitrogen and phosphorus discharges may be significantly reduced. (See later description in this chapter, Chapter 12, and MA *Policy Responses,* Chapter 10.)

15.2.2 Development-related Wastes

The amount of consumer or municipal waste produced on a per capita basis has a relationship with the development status of countries. (See Figure 15.1.) In general, poverty reduction would be expected to increase the production of consumer waste even without increasing populations. However, policies and practices may also significantly affect the amount and types of municipal wastes produced as societies develop.

The density and character of solid municipal wastes also differs at different states of development. (See Figure 15.2.) In the United States and Europe, for example, solid waste has a large fraction of light materials, such as carton boxes, paper bags, and plastic bags, whereas in many developing countries there is a larger fraction of higher density solid waste, such as gravels, glass, food wastes, and unusable metals.

There are three different types of agricultural wastes: fertilizers, pesticides, and organic wastes (such as manure). The use patterns of these are different and typically depend on a country's state of development. In industrial nations, fertilizers were applied in increasing amounts per unit area until the late 1980s, when application declined. (See Figure 15.3.) Recognizing the contribution of agricultural runoff to degraded water quality and eutrophication and the expense of unnecessary overfertilization, improved farming practices were introduced in many countries, which reduced the need for more fertilization yet maintained production. In contrast, in many developing countries the application of fertilizer on an area basis is still increasing and has surpassed the rate in industrial countries. There is, however, considerable variation between industrial and developing countries: industrial ones use more pesticides overall. (See Figure 15.4). Hidden within this overall trend are some additional important trends:

- Industrial countries are quicker to move to newer, less toxic (to humans), more environmentally suitable systems and products.
- Developing countries are often still using older, less expensive, more toxic pesticides at significant risk to farm workers, their families, and others in the vicinity of farms (Goldman and Tran 2002), with poverty exasperating such problems.
- Many developing countries have stockpiled wastes that are likely to eventually breach containment and be a source of potential harm if not destroyed or disposed of properly (Goldman and Tran 2002), again a problem exasperated by poverty, which reduces the capacity to deal with such problems.

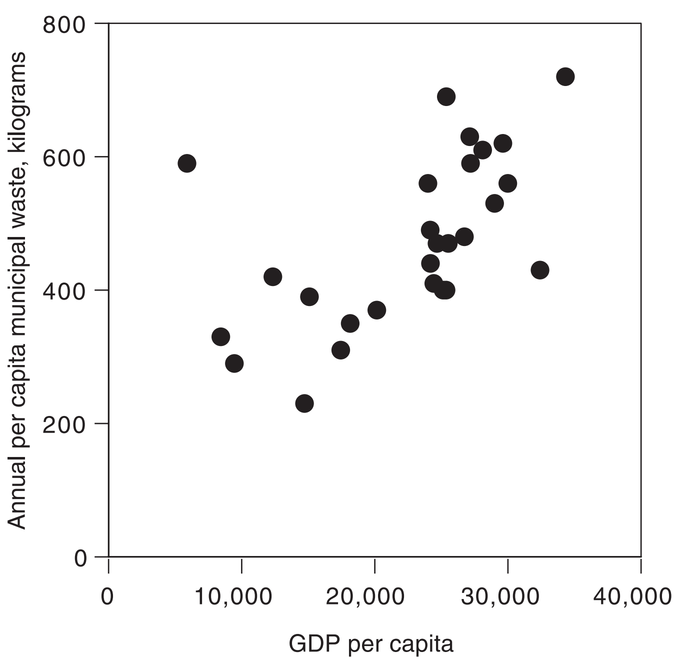

Figure 15.1. Municipal Waste Production in OECD Countries by per Capita GDP (Harrison and Pearce 2001; UNDP 2003)

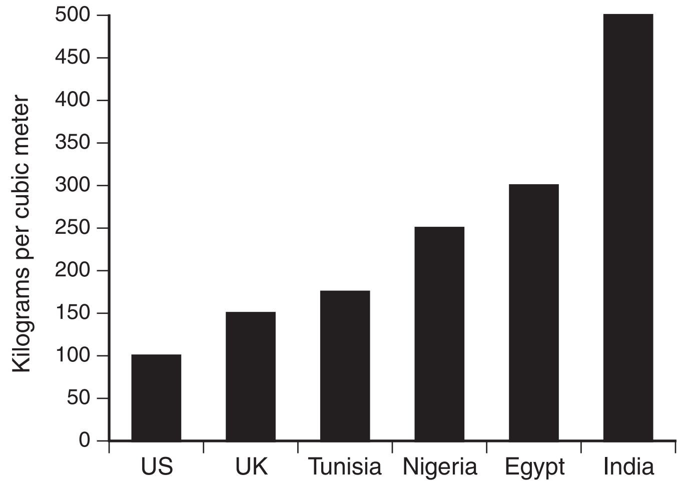

Figure 15.2. Density of Municipal Solid Waste in Selected Countries (UNEP 1996)

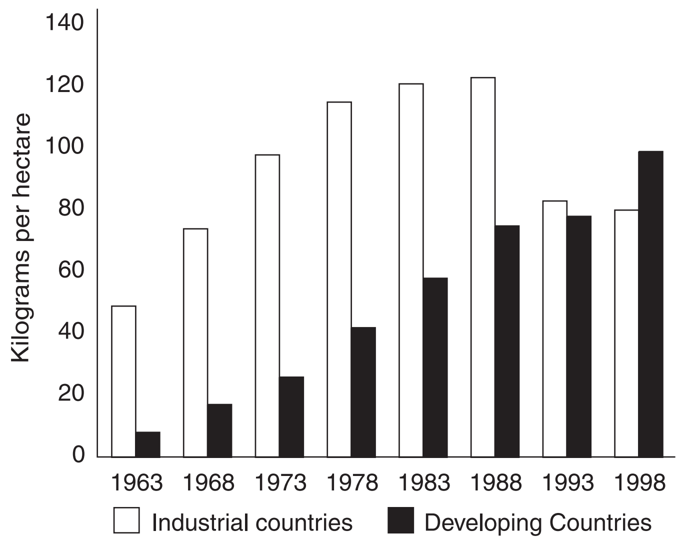

Figure 15.3. Fertilizer Use Trends in Industrial and Developing Countries, 1963–98 (Harrison and Pearce 2001)

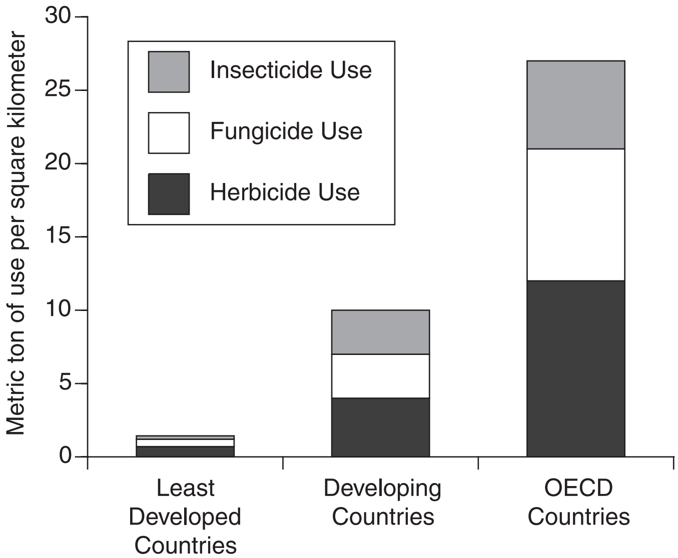

Figure 15.4. Pesticide Use in Countries at Different Levels of Development (Goldman and Tran 2002)

- Many individuals applying pesticides, particularly in developing countries, lack appropriate training. This leads to pesticide poisonings, unnecessary use, and misapplication of pesticides.

15.2.3 Wastes Controlled by Regulations

The amount of industrial wastes produced can be controlled by regulation and good industrial manufacturing practices, and it is not necessarily the case that discharge of industrial wastes grows with increased industrial levels. Figure 15.5 shows that releases of industrial wastes to water do not increase in proportion to the gross domestic product of various countries. The trend is not significantly different if looking only at the waste produced as a function of the fraction of GDP that is attributable to the industry sector.

The prevention of industrial discharges can be required by a strong regulatory framework and can be achieved through treatment of waste streams (or pollution control) and through pollution prevention (often called ''green chemistry'') through modification or selection of manufacturing processes to reduce or eliminate the production of wastes in the manufacturing process while providing the same products (Greer 2000).

15.2.4 Wastes Controlled by a Combination of Factors

Some wastes do not fit into a single one of the categories just described. For example, emissions from cars and trucks include carbon monoxide, reactive forms of nitrogen, soot, PAH, and carbon dioxide. The number of vehicles in any country depends on population size, the wealth of the population, and the policies in place. The emissions from an individual vehicle depend on regulation and enforcement of emission standards and on the kinds of vehicles (that is, the size and engine capacity and type) in use.

15.3 The Necessity of Waste Management

The production of wastes is a normal function of all living organisms, and individuals, groups of organisms, and societies depend on the capacity of ecosystems to detoxify such wastes. Without

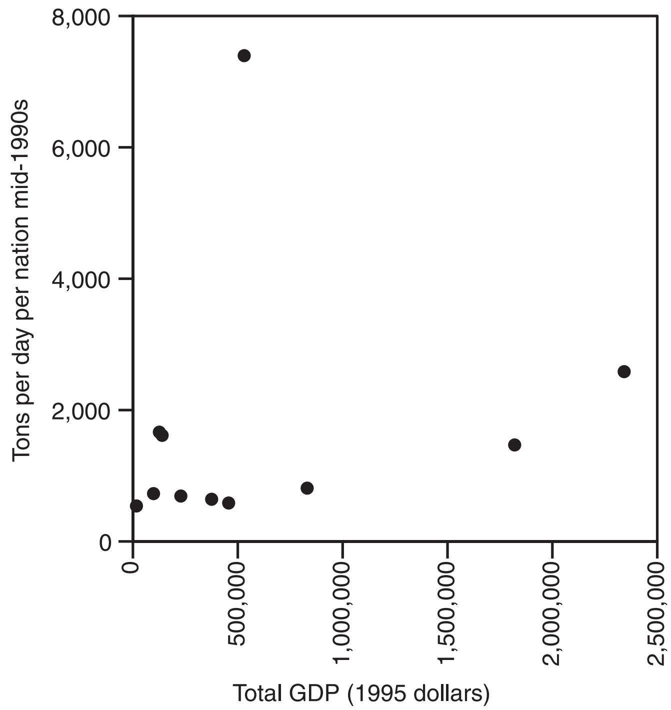

Figure 15.5. National Releases of Organic Water Pollutants in Selected Countries. The nations included (in order of lowest to highest GDP) are Ukraine, Indonesia, Russia, India, Brazil, China, United Kingdom, France, Germany, Japan, and United States. (Harrison and Pearce 2000; WRI 2003)

an ability to manage wastes, organisms cannot live indefinitely. A lesson often taught in introductory biology classes provides a useful illustration. Bacteria inoculated into a rich culture medium will at first grow and multiply. But eventually, as waste products from bacterial metabolism build up in the medium, the bacteria can no longer multiply and may die. The death happens even though there may still be plenty of food for the bacteria. They are poisoned by their wastes.

Higher organisms require systems to process wastes and expend significant energy to deal with wastes. For example, a human body has kidneys, liver, large intestine, and bladder that are primarily committed to waste processing. Further, the circulatory system is just as important for transporting wastes to be processed or eliminated as it is for carrying oxygen and nutrients to cells. Waste management is an important and necessary function of higher organisms.

Similarly, a portion of society's energy must be committed to the important but unglamorous task of waste processing in order to promote health and well-being. In a human-dominated Earth, the practice of placing wastes out of reach is no longer a long-term solution. The dumping of wastes, such as at sea, or the transport of wastes from one country to another does not necessarily prevent the wastes from causing human detriment.

15.3.1 Local Scale

On the scale of a large city, sewage treatment and solid waste management are particularly important functions. The level of commitment necessary to accomplish these tasks may be illustrated by examination of the expenditures in cities where sewage and solid waste services are considered adequate. In an examination of budgets for some major U.S. cities, for example, the combined expenditures of solid waste disposal and sewage treatment range from about half the costs of police and fire protection (New York and San Diego) to equal to those expenditures (Detroit and Houston). Establishing effective waste management functions is an extremely important development goal, as the poor are particularly susceptible to detrimental exposure to wastes (Goldman and Tran 2002; see also description later in this chapter).

15.3.2 National Scale

Regulatory management of wastes is generally conducted through national governments and through state or provincial authorities. Insufficient regulatory management often leads to human health impairment, economic loss, or ecosystem degradation. The costs of failure to prevent waste problems can be very high, especially those for cleaning up contaminated sites. For example, the U.S. Environmental Protection Agency estimated (EPA 1998) that it would require $32.9 billion in public funds to remediate the 5,664 listed contaminated sites in the United States at that time, which is in addition to the considerable private funds spent on these projects. Another example is the costs of remediation in U.S. coastal waters, where it is estimated that upgrading sewage treatment plants to mitigate nitrogen-caused low oxygen problems in estuaries will cost up to $20 billion for the Chesapeake Bay and about $10 billion for Long Island Sound (Boesch 1996). In addition to such remediation costs, the full cost of failure in waste management includes broader human, ecosystem, and economic costs.

15.3.3 Global Scale

Some contaminants are of global significance, particularly persistent chemicals subject to long-range transport. Accordingly, a number of international conventions and protocols have come into force or been signed to manage such chemicals. Notable among these are:

- the 1979 Geneva Convention on Long-Range Transboundary Air Pollution and its eight protocols;
- the 1985 Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol on Substances that Deplete the Ozone Layer (plus amendments);
- the 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal;
- the 1992 United Nations Framework Convention on Climate Change and its Kyoto Protocol;
- the 1998 Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade; and
- the 2001 Stockholm Convention on Persistent Organic Pollutants.

In addition, there are further efforts to manage chemicals on a global basis, such as the U.N.'s Strategic Approach to International Chemicals Management initiative.

15.4 The Capacity of Ecosystems to Detoxify or Use Wastes

The ability of an ecosystem to reduce waste concentrations depends on both the properties of the waste and the properties of the ecosystem. In order to understand the potential harm of a waste or to determine how much capacity an ecosystem has to assimilate a particular waste, it is necessary to examine the ecosystem processes that are responsible for the fates of wastes. Although there are thousands of types of materials in wastes, ecosystem processes are relatively few in number.

Table 15.2 lists the ecosystem processes that may act to reduce the concentrations or impacts of wastes in an environment over time. There are two fundamentally different types of processes:

- *Processes that act to change wastes into less toxic forms (''detoxification'')*: Some types of wastes may be completely destroyed by processes in the environment or used in the environment in a way that renders them harmless. It should be recognized that while processes that alter waste materials are often on the path to detoxification, the initial alteration of a waste may not reduce the potential of the waste to do harm.
- *Processes that move and transport wastes*: These reduce concentrations of waste by diluting them into larger areas or larger volumes of water. However, some waste transport processes may also concentrate wastes into ''hot spots'' of relatively high waste concentrations.

Different types of waste have different properties and interact with or are subject to different environmental processes. Table 15.3 lists the general detoxification characteristics for different types of waste materials.

15.4.1 Detoxification Processes

15.4.1.1 Microbial Degradation

Organic wastes can usually be broken down or even consumed as food by some organisms. When degraded, the waste may be made less toxic and its harmful effects reduced. Remineralization is the complete breakdown of an organic chemical (for example, into its basic components such as carbon dioxide, nitrogen, phosphorus, and water), such as may occur by microbial digestion. Remineralization completely destroys toxicity inherent in such waste. Most remineralization is conducted by microbes (primarily bacteria and fungi).

The ability of microbes to metabolize and remineralize different wastes is highly variable. Remineralization depends on the type and number of microbes in the total community that are capable of degrading a particular waste. The number of waste-degrading microbes in turn depends on prior exposure to the waste (or similar types of waste) through chronic or single-event exposures. Degradation of the wastes may increase after exposure as a result of an increase in number of waste-degrading microbes or the induction of appropriate enzyme systems.

The rates at which microbes can degrade wastes are influenced by temperature and thus may change seasonally. The presence of oxygen often exerts a strong influence on degradation rates, and wastes may persist for very long periods of time in sediments that have little or no oxygen, even though microbes in oxygen-rich environments may readily degrade the same waste. Marine and aquatic sediments and water-saturated soils in wetlands are often low in oxygen. Hence, the water availability in a specific location, acting through changes in the amount of saturated sediments and soils or even through changes in soil moisture, may have significant effects on contaminant degradation rates.

Some wastes break down in anaerobic conditions. Specifically, the removal of chlorine atoms from PCB molecules, a necessary first step in their remineralization, seems to occur (though slowly) in anaerobic conditions (e.g., Mondello et al. 1997).

High concentrations of waste contaminants may also be toxic to the bacteria and fungi that could otherwise degrade the contaminant were it present in lower concentrations. This restricts the breakdown of a contaminant to the less contaminated areas of a site, slowing the overall degradation.

Table 15.2. Processes Involved in Waste Processing and Detoxification

Processes	Factors Affecting Processes
Contaminant movements in soils	
Sorption to sediments (may reduce bioavailability)	chemical nature of soils; especially organic content and cation exchange capacity, basicity of compound
Leaching by precipitation water flow (transport from and through surface sediments)	porosity of soils, rate and pattern of rainfall, vegetation cover, slope of soil surface, polarity of compound
Groundwater transport	clay content, cation exchange capacity, porosity, hydraulic gradient, polarity of compound
Volatilization and dust transport	vapor pressure of chemical, vegetation cover, moisture content of soils
Soil erosion	vegetation cover, soil moisture content, soil cohesion
Biological transports	bioturbation, bioconcentration, and animal movements and migration
Contaminant movements in water bodies	
Mixing or dilution	volume of receiving waters, stratification
Advection and dispersion	velocity of water, turbulence regime
Water residence time	water input rate, tidal height, salinity distribution
Particle and sediment interactions and scavenging to sediments	solubility of contaminant (Kow), particle deposition rate
Sediment-water exchange	diffusion rate, bioturbation rate, water level fluctuations
Sequestering of chemicals (acid volatile sulfides in sediments)	oxidation state of sediments, availability of sulfides
Scavenging to (accumulation at) sea–air interface	solubility of contaminant
Volatilization	vapor pressure of contaminant, wind speed and water surface roughness
Aerosol formation	breaking waves
Precipitation from solution	solubility limits
Biological transports	uptake by organisms, settling of organic materials, food chain transfers
Contaminant movements in air	
Wind transport	wind speed, particle size and density
Wet deposition	precipitation patterns and solubility
Dry deposition and adsorption	surface area, air turbulence, "strictness" of contaminant
Processes responsible for alteration and destruction of contaminants	
Direct photolysis	strength and wavelength of light
Oxidation/reduction	properties of chemicals, oxidation state of media
Acid, base, and neutral hydrolysis	properties of chemicals, moisture availability
Microbial transformations	type of chemical bonds (e.g., chlorinated/holgenated vs. natural compounds); native community of microbial degraders; microbial degradation rates may depend upon waste concentration, temperature, the presence or absence of oxygen, pH, prior exposure, availability of co-metabolites, and influence of synergism
Radioactive decay	rate of decay intrinsic to radionuclide
Die-off (of pathogens and indicator organisms)	temperature and other conditions in environment, presence of organisms to ingest pathogens, presence of vector organisms

Chemicals that can be used as food by microbes tend to break down more quickly than poor food-quality chemicals. Some organic chemicals are especially slow to break down in the environment. For many of these, their resistance to microbial degradation results from the presence of many attached chlorine or bromine atoms. While there are many naturally occurring organic compounds incorporating chlorine or bromine—which degrade, albeit slowly, naturally—many of those synthesized by the chemical industry are quite resistant to microbial degradation. The chlorine-carbon bonds in these synthetic chemicals are not naturally abundant, and organisms do not have enzymes effective at degrading these chemicals. One group of such resistant chemicals with known toxic effects are the persistent organic pollutants, some of which have been banned from further production by international treaties (as described earlier in this chapter).

The time required for the concentration of POPs in a contaminated area to decrease measurably is typically measured in decades (Wania and Mackay 1995). For example, results from the NOAA Mussel Watch Program show that PCBs (one group of POPs) in Delaware Bay are decreasing at a rate of only about 5% per year (a half-life of about 13 years). This decrease is partly due to slow degradation of the PCBs but also to their dilution and spreading. On a national scale, the average PCB concentration in mussels in the United States is only decreasing at a rate of 2% per year (a half-life of 34 years). Another example is dioxin contamination in Viet Nam, which was a result of defoliant use between 1962 and 1970. Concentrations of dioxin in human milk in Viet Nam have been decreasing with a half-life of about 4 years (calculated from data in Schecter et al. 1995). This decrease is a result of both degradation and slow dispersion of the dioxin. The slow rate of loss, coupled with the high initial exposures, results in dioxin concentrations in human milk some 30 years after the contamination ceased that are still 10 times higher than in nonexposed areas (Schecter et al. 1995).

Where large amounts of waste are present, such as in an oil spill, the degradation rates of the wastes may be limited by factors needed for microbial growth such as nitrogen and phosphorus. If bacteria cannot increase in number, the degradation rates of compounds will remain slow. The physical nature of spills may also inhibit microbial breakdown. If the spilled waste remains in large clumps, or patches, the microbes cannot reach or degrade the interior of the clump, and only the surface of the clump is subject to microbial decay, greatly slowing the digestion of the waste.

For many organic wastes, and particularly large (high molecular weight) compounds, it is important to distinguish between an initial alteration of the chemicals in the waste (a relatively small change in the form of the waste) and complete remineralization. A small alteration of a parent compound may result in persistent and/or toxic daughter products that may be of as much concern as the parent waste chemical.

With such a complex array of factors that can influence biodegradation, it is not usually a simple matter to predict the persistence of a degradable waste in an environment. However, experience with wastes has been gained and models have been developed that allow such predictions to be made with good confidence. In addition, understanding of the process affecting waste degradation has allowed the development of bioremediation techniques that create the right conditions to accelerate biodegradation in some contaminated areas (Alexander 1994) (see MA *Policy Responses,* Chapter 10).

15.4.1.2 Pathogen Die-off

Some human pathogens are rendered harmless in the environment. Many bacteria and some viruses that only grow in condi-

Table 15.3. Detoxification Characteristics for Different Types of Waste Materials. For the types of waste that cannot be destroyed by natural environmental processes, as opposed to dilution or sequestration, no time frame for detoxification is given. Half-life is the time it takes for the concentration of a particular material to reduce by half. The use of half-life is a measure that implies first-order kinetics. It should be recognized that detoxification is usually a biological process that will have much more complex kinetics than first-order. Nevertheless, half-life is a useful simplifying approach.

Type of Waste	Characteristics of Waste and Major Processes for Detoxification	Time Frames for Detoxification, Where Applicable
Airborne sulfur dioxide and sulfates	Component of acid rain. Can be buffered by some soils until buffering capacity of soils is exceeded.	
Airborne oxides of nitrogen	Component of acid rain. Contributor to eutrophication. (see box on eutrophication.)	
Polycyclic aromatic hydrocarbons (PAH)	Many PAH are carcinogenic. PAH may be photodegraded and remineralized by microbes. Many PAH have a high affinity to adsorb onto particles and soils.	Rate of photodegredation of PAH depends upon specific configuration of individual PAH. In air or sunlit waters, half-lives of PAH may range from hours to days. Lower molecular weight PAH can be readily degraded in aerobic soils and sediments, with typical half-lives in days to weeks. Higher molecular weight PAH degrade much more slowly, with half-lives in weeks to months. In anaerobic conditions, PAH may persist indefinitely.
Toxic metals, especially mercury, lead, and cadmium	Cannot be degraded. May be bound to other material (i.e., sulfides) in certain conditions so that toxicity of metals is not exhibited if there is sufficient binding material. Other binding sites include organics, and they may form precipitates such as hydroxides and oxy-hydroxides that may render them less bio-available and in the process reduce their toxicity.	Rate of dilution depends upon environmental setting, while precipitation processes are pH/redox regulated. Many metal-contaminated sites may remain contaminated for decades to centuries.
Halogenated organic compounds, especially DDT and its metabolites, PCB, PCT, dieldrin, and short-chained halogenated aliphatic compounds	Some can be photodegraded. May be degraded by microbes. Many have high affinity to adsorb onto particles and soils. One route of degradation is the volatilization of chemicals from sediments or soils to the atmosphere, where it is degraded by strong UV light.	Due to having halogen-carbon bonds that only occur in trace amounts in nature, microbes do not generally have an ability to degrade these compounds readily. However, general detoxification enzymes within microbes can degrade some of these chemicals, albeit slowly. For example, half-lives of PCBs in contaminated sediments are typically decades.
Petroleum hydrocarbons	Petroleum hydrocarbons are a mixture of primarily alkane compounds and PAH. The alkanes are readily degraded by microbes in the right conditions. PAH are described above. Where petroleum hydrocarbons are introduced into the environment in large quantity, such as an oil spill, the oil may remain in large drops so that bacteria cannot get to most of the oil. In large spills, there may not be sufficient nitrogen and phosphorus in the local environment to permit hydrocarbon-degrading microbes to multiply.	Lighter hydrocarbons can degrade with half-lives of hours to days when found in low concentrations and in aerobic conditions. Heavier components of oil—i.e., that left over after the light hydrocarbons are degraded or volatilized—can persist indefinitely (such as tarballs). Light or heavy hydrocarbons in anaerobic conditions will degrade very slowly if at all. In addition, high concentrations of hydrocarbons may initially exhibit localized toxic effects, causing a delay before degradation proceeds.
Toxins of biological origin from algae, fungi, and bacteria	Presumably these compounds are subject to microbial and/or photodegradation.	Rates of degradation probably rapid, with half-lives in hours or days. The toxicity of a water body disappears soon after the organisms producing the toxins are no longer present.

(continues over)

tions found in the human body lose viability in the relatively harsh conditions of the environment. Both viruses and bacteria may be ingested and utilized for food (therefore remineralized) by other organisms in the environment without detrimental effects. However, other pathogens, such as vector-borne diseases, complete part of their life cycles outside of the human body and are maintained by their in hosts in the environment.

15.4.1.3 Photochemical Degradation

In the atmosphere, and to a lesser extent in surface waters, some compounds are altered by interaction with ultraviolet light or by chemically reactive compounds produced by ultraviolet light, such as ozone or hydroxyl radicals. Some limited groups of organic chemicals have structures (chromophores) that adsorb light energy and are activated into a particularly reactive state, altering their structure. This structural change may not reduce the toxicity and may even create more toxic daughter products, but it may be a first step toward remineralization, which can be followed by microbial degradation. The rates of alteration by photochemical degradation may vary widely between chemicals that have only slightly different structures. Reactive compounds in the atmosphere, especially ozone, may also act to alter the structure of airborne wastes.

15.4.1.4 Sequestration of Wastes

Some waste materials may be sequestered in the environment in such a way that they are not biologically available and do not exhibit toxicity. The sequestration of certain metals in marine and

Table 15.3. ***continued***

Type of Waste	Characteristics of Waste and Major Processes for Detoxification	Time Frames for Detoxification, Where Applicable
Nitrogen compounds	Nitrogen exists in different forms and is an essential plant nutrient. The presence of elevated nitrogen concentrations in water can lead to proliferation of algae and other plant species. This can reduce the value of the resource and can affect human health. For example, nitrate levels over 20mg/l are considered the safe upper limit in potable water.	Rates of transformation are dependent on the form. Dentrification can be rapid (hours) in the presence of bio-available carbon and acceptable pH and temperature conditions. Assimilation into plant biomass is light-, temperature-, and plant species-dependent and may be hours to days.
Ammonia toxicity	Ammonia is oxidized to nitrate in aerobic environments. Local pH and salinity conditions can influence the level of toxicity by influencing the ionized and un-ionized fractions.	Rate of oxidation is temperature and oxygen-dependent, with typical half-lives of hours to days.
Phosphorus	An important plant nutrient that is associated with fertilizers and detergents. Phosphates bind with some metals, for example iron and aluminum salts, and can from insoluble salts of calcium and magnesium under high pH conditions in oxidizing conditions. Reducing conditions can result in the release of preciously bound phosphorus. Phosphorus may be removed by plant uptake.	Minutes to hours if chemical precipitation/release processes are involved; days to months in the case of biological uptake being species-dependent.
Organic loading	Most organic matter can be remineralized to carbon dioxide by microbes. Some organic matter is resistant and will degrade much more slowly.	Rate of oxidation is temperature and oxygen-dependent, with typical half lives of hours to days for readily degradable organics and months to years for resistant materials.
Acid wastes	High acid wastes (i.e., low pH wastes) can result in the mobilization of metals that may increase toxicity. Acidity can be buffered in both soils and water until the buffering capacity is exceeded. The presence of sulfur can influence acidity, for example the oxidation of sulfur compounds can lead to a reduction in pH while sulfate reduction through the generation of alkalinity can reduce the acidity , which can be reflected in an increase in the pH.	Hours to weeks if conditions are favorable. Chemical processes are generally more rapid than biologically mediated processes.
Pathogens	Some pathogens may lose viability in environment or may be utilized as food by other organisms. Some pathogens are endemic in the environment and do not lose viability.	Survival half-lives of non-endemic pathogens is typically hours to days.
Radionuclides	Natural radioactive decay to stable isotopes (see metals for associated processes).	Half-lives of most medical-use radionuclides range from hours to weeks. Half-lives for the bulk of radioactive wastes from power plants range from decades to millennia.
Solid salts of alkali metals and alkaline earth metals	Cannot be destroyed.	
Waste heat	Heat loss occurs through dilution and radiation of heat energy to the atmosphere.	

aquatic sediments by acid volatile sulfides is an example. These metals are bound into a mineral form that is not biologically available, and as long as there are sufficient sulfides to bind all the metals, no toxicity is exhibited (Ditoro et al. 1992). Where the concentrations of metals exceed that of sulfides, the sediments exhibit toxicity. Sequestration may be reversible. If conditions are altered, the sequestration may break down and the wastes returned to toxic forms. In the case of acid volatile sulfides, the metal sequestration takes place in anoxic sediments, and if the sediments become oxidized through disturbance or ecosystem change, the metals may be released from their bound state and become available and exhibit toxicity. Some chemicals may also be sequestered within soil or sediment organic matter.

Humans often manage wastes by sequestration or immobilization, such as in managed landfills or high-level radioactive waste storage sites. As with natural sequestration, sufficient time may bring about a change in conditions and release wastes back to the environment.

15.4.1.5 Incineration

Organic wastes are often remineralized by incineration. Efficient incineration can completely destroy the toxicity of an organic or pathogenic waste. Inefficient incineration, however, results in the production of carcinogenic polycyclic aromatic hydrocarbons, dioxins, and furans. If a metal-containing waste is burned, the metals may be emitted to the atmosphere, where they can enter food chains and cause environmental damage and detriment to human health. Incineration in large amounts, especially of sulfur-containing materials (such as some coals) can add acidity to the atmosphere, resulting in acid rain and ecosystem damage. A variety of engineering techniques are available to capture the contaminants and reduce the emissions.

15.4.2 Waste Transport Processes

As noted earlier, there are a number of processes that tend to disperse materials in the environment—for example, pesticide leaching into groundwater, runoff with rainwater to water courses, and evaporation or volatilization into the atmosphere, where it may be carried by winds. Soil and wind erosion may also carry pesticides sorbed to soil particles into water bodies and to downwind areas.

Reduction of waste concentrations in a single body of water is best understood as a result of two processes: dispersion (dilution by mixing into larger volumes of water) and advection (water moving downstream). Both these processes reduce the concentration of the waste at its point of entry in the ecosystem. These also apply to contaminants in air.

Dispersion and advection have been counted on for millennia to manage human wastes. If the wastes can be detoxified by the environment, and the loading rates do not exceed the capacity of the environment to process them without undesirable change to the ecosystem, such an approach can be effective. However, with increasing human population densities and waste loads, coupled with many types of wastes that do not degrade rapidly, such a simple approach is rarely adequate. Even wastes that are diluted into the entire atmosphere of the planet have reached concentrations above acceptable levels. Examples are the upper-atmosphere ozone-depleting chemicals chlorofluorocarbons and methyl bromide, which are now the subject of coordinated efforts to reduce their emissions through the Vienna Convention and the Montreal Protocol.

While there is a natural tendency for all things to disperse and move from areas of high concentration to low concentration, there are also processes that effectively act to concentrate some wastes and create relative hot spots. The next two sections examine these processes in more detail.

15.4.2.1 Partitioning and Scavenging

One particularly important process that influences the fate of chemicals, especially in aquatic systems, is that of chemical partitioning. Many waste chemicals have low solubility in water. Even when present in water at concentrations below their absolute solubility, low-solubility chemicals may be strongly attracted to particles. If a solid surface is available, such as small particles in the water, the chemical will tend to adsorb or attach to the particle. The strength of this affinity is referred to as a partition coefficient (which for organic chemicals correlates with the octanol/water partition coefficient, or Kow). Some authors express this general concentration mechanism as ''solvent switching'' (MacDonald et al. 2002). The particle affinity of metals depends on other factors, especially the oxidation state of the metal.

Particles in the water column tend to settle to the bottom. This may occur in standing water or in areas of low flow, such as upstream of a dam in a river. The adsorption of chemicals to particles and the subsequent settling of particles acts to transport (or scavenge) chemicals from the water column to sediments. In this fashion, relatively high concentrations of chemicals can build up in sediments even in areas that originally had dilute concentrations of waste in the water. The sediments act as a reservoir for wastes, often to the detriment of benthic organisms. And depending on the persistence of the waste, the sediments may remain contaminated even if the inputs are stopped. If the sediments are disturbed by high water flows such as floods or major storms or by mechanical means such as dredging or construction projects, the sediments may become ''new'' sources for wastes.

15.4.2.2 Biological Uptake and Trophic-level Concentration

Many waste chemicals may have a strong affinity for biological tissue, particularly for the lipid (fatty) tissues in organisms. An aquatic organism may move large amounts of water across its metabolic surfaces (gills or equivalent) in order to obtain oxygen. This provides an opportunity for chemicals (especially organic compounds such as the POPs) to be taken up into the organism, concentrating the chemical by another type of solvent switching. As with sediment partitioning, the concentrations in the organism may become much higher than in the water. The magnitude of this effect is usually described as the ''bioconcentration factor.''

The concentrations of wastes can increase in organisms further up the food chain. This process is often called ''bioamplification'' and may be viewed as a ''solvent depletion process'' (MacDonald et al. 2002). (Biomagnification is another term often used in the same sense as bioamplification, although biomagnification is also sometimes used in the same sense as bioconcentration. The use of these terms is not standard.) When a higher trophic level organism ingests a food that has been contaminated (by bioaccumulation), it may digest most of the food but none of the waste. The waste then becomes much more concentrated in the gut, exposing the higher-trophic-level organism to high concentrations of waste. Where upper-trophic-level organisms cannot metabolize or excrete the waste, the waste increases in concentration in bodies of organisms in successively higher trophic levels, and thus bioamplifies. In this fashion, persistent chemicals that were originally present at low, nonharmful levels in the environment build up to harmful levels in the tissues of higher-trophic-level organisms, including humans (MacDonald et al. 2002).

15.5 Determining the Capacity of an Ecosystem to Assimilate Wastes

The assimilative capacity of an ecosystem to adsorb waste may be defined as the amount and rate of a given waste that can be added to an ecosystem before some specified level of detrimental effect is reached. Deciding on a safe or acceptable level is not usually a simple matter, as is clear from the complex set of processes and the wide array of possible waste types just described. Further, the ''acceptable level'' incorporates human value judgments, which may be different for different people and may vary over time.

The human value judgments include such considerations as:

- the level of risk that is acceptable;
- whether environmental standards are based upon some absolute level or whether risks are balanced against benefits;
- the costs of mitigating the effects of wastes;
- the manner in which noneconomic properties of an ecosystem are valued; and
- the allocation of benefits, or risks, to different sectors of Earth's population, and between the present and the future.

Hence the capacity of an ecosystem to assimilate wastes is not usually determined by purely scientific or objective study. Science may be able to clearly describe the consequences of any particular waste loading, but it is the application of human values to the consequences that are responsible for setting a ''safe'' or acceptable limit.

15.5.1 Safe Levels of Exposure

The concept of ''safe'' is reasonably clear for pathogen wastes. If the disease organism is present in water or food, it is not safe to drink the water or eat the food. In practice, however, it is often not easy or routine to directly detect the presence of disease organisms in the environment. A separate test or procedure might be necessary for each species of pathogen, and the culturing of pathogens for test purposes is often difficult and may be dangerous. The presence of nonharmful organisms that are found in human wastes and that are relatively easy to measure are usually used to indicate the possible presence of disease organisms. This approach assumes that pathogenic organisms do not survive longer in the environment than do the indicator organisms, which may not always be the case. Still, the use of indicator organisms has been effective (but not perfect) in protecting human health for many decades. The common use of fecal bacteria for indicators is not useful in predicting the presence of parasitic worms.

Chemical wastes are often divided into two categories: those having threshold effects and those having no threshold effects. For threshold chemicals, there are assumed to be no detrimental effects below a certain level of human exposure, although above that threshold, detrimental effects may be found. For no-threshold chemicals, primarily carcinogens, it is usually assumed that there is detriment at all levels of exposure, no matter how small. For these, the probability of damage is greater with greater levels of exposure.

Establishing a safe level for a contaminant that has a distinct threshold effect is conceptually straightforward, but there may be considerable technical complexities in arriving at a standard, such as how to apply results of laboratory animal studies to humans. In practice, maximum exposure limits are usually set well below the threshold level for the observed effect in order to account for uncertainties in the measurement of the threshold, individual sensitivity, and the possibility of greater than estimated exposures to a waste for some persons. There is always some concern that a chemical may have subtle detrimental effects at low levels of exposure that are hard to identify as being caused by the chemical.

For non-threshold carcinogenic chemicals and for ionizing radiation, the risk increases with exposure. The effects are an increase in probability that the exposed person could get a cancer during his or her lifetime. As cancers may arise from different causes, the cause of a particular case of cancer may not be unequivocally attributable to a particular exposure, and the effects are observed in population statistics of how many persons contract cancer of a particular type. The setting of a "safe" level for a carcinogen requires a value judgment of the level of risk that persons are willing to accept, plus the knowledge of the probability of a cancer developing in an individual from a given dose (that is, the dose-response relationship). An example might be the standard for acceptable concentration of a chemical in drinking water. This standard may be based on a value of an individual's lifetime risk being no more than one chance in a million (usually used by U.S. EPA) or one in 100,000 (usually used by WHO) of contracting cancer from that chemical if they have a lifetime exposure to the chemical at the level of the standard.

The level of exposure that is deemed acceptable varies considerably from chemical to chemical depending on its toxicity. For example, the FAO/WHO *CODEX Alimentarius* standards for maximum residue levels range from 0.05 to 25 milligrams per kilogram for different pesticides on apples.

Where contaminants occur together and have similar mechanisms of detrimental effects, these effects may be additive, acting together so the threshold for effect may be reached at levels that would have no effect for individual chemicals. There is also concern that the effects of some contaminants may be synergistic in that exposure to a combination of two or more contaminants will lead to a much greater effect than would be expected from the simple addition of the effects of the individual contaminants. Finally, the effects of some contaminants may be antagonistic in that together there is less effect than would be expected from the addition of multiple contaminants (Yang 1994).

15.5.2 Predicting and Managing the Risks of Wastes

Determination of human health impairment from exposure to wastes can be very complex. For each waste or each component of a mixed waste stream, an evaluation of the impairment depends on a knowledge of the fate of the wastes in the environment, how much exposure humans will get from the waste, and how much detriment will occur from a given level of exposure.

In evaluating the detrimental effects of a waste or actions taken to reduce exposure and detriment from wastes, it is usually desirable to evaluate the total number of exposed persons in the population—the cumulative human-health impairment. For example, two differing waste management options might protect all individuals from exposures that exceeded standards for individual protection, but the options may differ in the total dose to the population.

Toxicology and risk assessment are developed areas of science, and various national and international bodies have used appropriate techniques to determine health risks and set appropriate standards and guidelines. Professional organizations working on these issues include the Environmental Mutagen Society, Genetic Toxicology Association, Society of Environmental Contamination and Toxicology, Society for Occupational and Environmental Health, and many others (see, for example, www.health.gov/environment/ehpcsites.htm). Although the scientific community has the ability in most cases to predict (with useful accuracy) the fate and effects of chemicals, due to the great number of possible contaminants (as well as the continuous generation of new compounds) and the fact that the specific conditions within a specific ecosystems may not be known, our understanding of the consequences of some contaminants is incomplete.

15.6 Drivers of Change in Waste Processing and Detoxification

At this stage it is not possible to state, on a global scale, whether the capacity of ecosystems will increase or decrease in response to climate change. The change in average local or global temperatures of a few degrees is not thought likely to have much effect on the distribution of waste materials in the environment (MacDonald et al. 2002) or on a temperature-dependent microbial degradation rate.

As described earlier, the capacity for an environment to assimilate wastes is highly dependent upon local conditions. The bacteria and other decomposing organisms that detoxify susceptible chemicals or reuse nutrient wastes are highly dependent upon local conditions such as oxygen availability, moisture, and temperature. Hence, changes in local climate may have significant effects of waste assimilation capacity of different ecosystems. The conditions at some locations may allow the microbial community to be better able to process certain types of wastes. Other locations may suffer a reduced inherent ability to detoxify.

Changing climatic conditions may also have an effect on the susceptibility of organisms to wastes. Organisms living near their physiological temperature limits may be particularly sensitive to stress from waste contaminants. In such cases, small temperature changes may cause significant differences in the effects of contaminants.

A safe generalization for virtually all types of wastes is that the ability of environments to detoxify them can be overwhelmed at high waste loading rates. If waste production increases with growing populations and improved development of nations proceeds faster than waste management efforts, then it seems likely that there will be an increasing number and size of locations on Earth where the detoxification capabilities of the ecosystem will be overwhelmed and waste concentrations will build up to the detriment of human well-being to damage ecosystems with a loss of biodiversity.

It is hard to predict with a high degree of confidence which environments will be most subject to impacts by different types of wastes. Nevertheless, Table 15.4 is an assessment of the likelihood of ecosystems receiving different types of wastes and contaminants. Table 15.5 lists a number of the driving forces acting at the local level and the effects those drivers will have on waste processing and detoxification.

15.7 Selected Waste Issues

This section describes some key waste issues. A great number of waste types and issues could be cited as examples, and it is not possible for this chapter to attempt to detail the entire scope of waste types and issues in similar detail. The selection here is merely representative of this range, and should not be interpreted as suggesting that these wastes are the most important to consider for future waste management actions.

15.7.1 Consumer Household Wastes and Hazardous Materials

15.7.1.1 Household Trash, a Mixed-waste Stream

A multitude of products are used by individual consumer households or in nonindustrial commercial settings. Many of these products generate trash and require disposal. These include food wastes, paper products, plastics, and metals and may also contain harmful chemicals. Depending on local practice, wastes may be combined or attempts may be made to keep the different materials separate. Food wastes, when kept separate, may be used as compost and for soil enrichment. Some paper products, plastics, glass, and metals can be recycled. What is not separated and reused must be disposed of. Once different types of materials are mixed (usually by the individuals or households generating the trash), it is much more difficult to separate them for reuse. Polyethylene wrappers, bags, or sheets are a major problem in Africa as they litter urban areas, are not biodegradable, and do not burn readily.

Common practices are to either landfill (dump) or incinerate the wastes. Both options have drawbacks. Landfilling permanently takes up space, often in short supply in areas of high population density. Improperly designed and managed landfills may attract vermin, may contaminate groundwater, become visual blights, and emit objectionable odors. Although portions of the organic materials in landfills may decay and generate the green-house gas methane (which could be collected and used as a resource), much of the disposed materials does not degrade and will effectively persist permanently.

Incineration generates air pollution, with the amount of pollution dependent upon the investment in technologies to reduce or capture emitted metals and other hazardous materials before they leave the smokestack (NRC 1999). Where open burning is used, the simplest form of incineration, there is no opportunity for recapture of harmful materials in the smoke. Clearly, keeping the different types of wastes separate and reusing those materials is beneficial relative to either landfilling or incineration. However, most community recycling programs reduce the total volume of the domestic waste stream by only 30–50%.

The amount of household refuse is likely to increase with increasing affluence of persons, as indicated earlier in Figure 15.1. There can also be differences in societal practices that would deviate from this trend. Another example of development-dependent use of materials is provided by the per capita use of paper in different countries. (See Figure 15.6).

In parts of the developing world, municipal waste collection is often very ineffective, and much of the wastes are dealt with by a network of urban wastepickers (Furedy 1990, 1994). In most cases, wastepicking is driven by poverty. Picking through wastes of more-affluent people provides access to resources of clothing, fuel, housing, and even jobs for the poorest. The waste stream can be mined for the raw materials to support small-scale industries, but the conditions for the waste pickers are usually very unhealthy (Yhdego 1991). There have been some efforts to organize wastepickers and improve waste collection efficiency, recycling, and conditions for the workers (Furedy 1992; LIFE 1995; Poerbo 1991).

15.7.1.2 Consumer-use Hazardous Materials

Consumers use many products that contain hazardous materials. A partial list of such products sorted into general categories includes the following:

- *Household cleaners*: bleach, ammonia, disinfectants, drain opener, furniture polish and wax, oven cleaner, spot remover
- *Laundry products*: laundry detergent, fabric softener, bleach, perchloroethylene
- *Lawn and garden products*: fertilizer, pesticides, herbicides, gasoline, oil
- *Home maintenance products*: paint, paint thinner, stains, varnish, adhesives, caulk
- *Pesticides*: insecticide, mothballs, pet spray and dip, rat and mouse poison, weed killer, disinfectant, flea collars, insect repellant
- *Health and beauty products*: hairspray, hair remover, fingernail polish, fingernail polish remover, hair coloring products, cosmetics, medications
- *Automotive products*: antifreeze, brake fluid, car wax and cleaners, gasoline, oil filters, transmission fluid, windshield washer fluid, lead-acid batteries, tires
- *Other*: charcoal briquettes, lighter fluid aerosol cans, art and craft materials, lighter fluid, pool chemicals, shoe polish, batteries, electronic components, light bulbs

Many of these products represent potential waste streams and potential impacts on the environment. In addition, some of them may have detrimental effects on sewage treatment systems, especially individual household septic systems. Consumer use may be a significant fraction of chemical use not usually associated with individual consumers. For example, nonagricultural uses of pesticides in the United States represents about 30% of total pesticide sales (Donaldson et al. 2002). At least one pesticide is used in 77% of U.S. households, with most households using multiple types of pesticides (Donaldson et al. 2002). Pesticides are used in homes for nuisance insect control, protection of structures, and (in some countries) for control of insect-borne diseases. The risks of pesticide use in the home are relatively large. Between 1981 an 1990, on average 20,000 pesticide exposures a year were reported in emergency rooms throughout the United States, with 82% of those reportedly due to exposure in the home (Blondell 1990).

Further, many of these products may end up in domestic wastes, as indicated. Where toxic materials are placed in landfills, they represent an additional hazard as they may leach into groundwater and render it unsafe for consumption.

15.7.2 Persistent Organic Pollutants

POPs are a category of waste of special concern because of their longevity and biological effects. One definition of POPs is pro-

Table 15.4. Assessment of the Likelihood of Ecosystems Receiving Different Types of Wastes and Contaminants

	Dryland		Inland Waters		Coastal Waters						
Contaminant	Industrial Country	Developing Country	Industrial Country	Developing Country	Industrial Country	Developing Country	Marine	Mountains	Polar	Forest	Urban
Airborne sulfur dioxide and sulfates	xxx	xxx	xxx	xxx	–	–	–	xxx	xxx	xxx	xx
Airborne oxides of nitrogen	xxx	xxx	xxx	xxx	xx	xx	x	x	–	x	xx
Polycyclic aromatic hydrocarbons	xx	x	xxx	xx	xxx	xxx	x	–	–	–	xx
Toxic metals, especially mercury, lead, and cadmium	xxx	xx	xxx	xxx	xxx	xxx	x	x	x	x	xx
Halogenated organic compounds, especially DDT and its metabolites, PCB, PCT, dieldrin, and short-chained halogenated aliphatic compounds	xxx	xxx	xxx	xxx	xx	xx	x	x	x	x	x
Petroleum hydrocarbons	xxx	xx	x	x	xxx	xxx	x	–	xx	x	x
Toxins of biological origin from algae, fungi, and bacteria	–	–	xxx	xxx	xx	xx	x	–	–	–	x
Eutrophication	–	–	xxx	xxx	xxx	xxx	x	–	–	–	x
Ammonia toxicity	–	xx	xxx	xxx	xx	xx	–	–	–	x	x
Organic loading	–	–	xxx	xxx	xxx	xxx	–	–	–	-	
Acid wastes	xx	xx	xx	xx	–	–	x	x	x		
Pathogens	x	x	xxx	xxx	x	xx	–	–	–	–	x
Selected indicators of water quality: biological/chemical oxygen demand, dissolved oxygen, pH, coliform bacteria	x	xxx	xx	xxx	xxx	xxx	x	–	–	–	–
Selected radionucleides	x	x	x	x	x	x	x	–	–	–	–
Solid salts of alkali metals and alkaline earth metals	xxx	xxx	xxx	xxx	–	–	–	–	–	–	–
Other substances that have caused significant local environmental problems in the past, such as arsenic, boron, elemental phosphorus, selenium, and fluoride	xxx	xx		xxx	xxx	xxx	–	–	–	–	–
Waste heat			xxx	xxx	xxx	xxx	–	–	–	–	–
Domestic refuse (mixed wastes)	xxx	xx	x	xx	x	x	x	–	–	–	xxx

Key:

xxx = highly probable
xx = moderately probable
x = somewhat probable
– = not likely or relevant

vided in the 1998 Aarhus Protocol on Persistent Organic Pollutants of the 1979 Geneva Convention on Long-Range Transboundary Air Pollution: "Persistent organic pollutants (POPs) are organic substances that: (i) possess toxic characteristics; (ii) are persistent; (iii) bioaccumulate; (iv) are prone to long-range transboundary atmospheric transport and deposition; and (v) are likely to cause significant adverse human health or environmental effects near to and distant from their sources."

Further production of these chemicals will be prohibited under international treaty. The Aarhus Protocol and the 2001 Stockholm Convention on Persistent Organic Pollutants ban the production of an initial list of POPs (12 under Stockholm and 16 under Aarhus), including pesticides, industrial chemicals, and industrial by-products, and include provisions for adding other chemicals to the restricted lists. The Aarhus Protocol has 36 signatories and went into force in October 2003. The Stockholm Convention has 151 signatories and entered into force in May 2004.

A common feature of POPs is that they are all heavily chlorinated compounds. Although there are numerous naturally produced chlorine and bromine compounds (Gribble 2003), they occur at low concentrations in ecosystems, and there are few naturally occurring enzymes and metabolic pathways efficient at breaking down these compounds. POPs have a low solubility in water and a high affinity

Table 15.5. Principal Drivers of Change Summarized from Individual Chapters, with a Provisional Assessment of the Implications for Detoxification

System	Driver of Change	Some Considerations for Detoxification
Cultivated systems	change in vegetation (seasonal contribution to inputs) change in exposure (erosion) temperature interruption in nutrient flow changes in moisture regime (irrigation) removal of biomass introduction of inorganic nutrients introduction of herbicides, pesticides salinization aquaculture in coastal areas floodplains (accreting systems) cultivation of floodplains change in soil structure	increase in soil loss with negative consequences for waste/contaminant attenuation due to loss of part of the resource the soil through erosion becomes a waste/contaminant in its own right causing accretion in and loss of wetlands; a change in the nutrient status of receiving water bodies due to P bound to soil and an increase in turbidity can reduce photosynthetic capacity of water, affecting nitrogen/phosphorus cycling possible greater ranges in temperature that affect moisture content (increase in evaporation losses) and rates of particular transformation processes by influencing metabolic rates cropping reduces return nutrient flows due to active removal of vegetation change in nature of nutrients from organically derived to inorganic due to fertilization direct addition of herbicides/pesticides to crops and transfer of these to other ecosystems either by aerosol or elution introduction of irrigation water can result in salinization of soil, if irrigation scheduling and drainage are not managed, etc.; irrigation return flows can result in an increase in salinity and nutrient flows into receiving waters introduction of ponds and fish farming can result in increase in waste loads in affected waters; the ponds themselves may assist in internal transformation processes afforded by the extended hydraulic retention periods regulated flows due to damming can result in dessication and loss of floodplain functionality, with sediments trapped in dams (rather than on floodplains); should the trapped sediments be subjected to anoxic/anaerobic conditions, previously bound phosphorus, for example, could be released and contribute to eutrophication cultivation of floodplains can result in loss of changes in carbon supply and have implications for nutrient cycling and retention change in soil structure and properties, i.e., loss of carbon, changes in carbon exchange capacity, pH, etc. can have implications for contaminant removal
Dryland systems	changes in vegetation cover increased nutrient load (livestock) use of wetlands (water) water retention (dams) change in exposure (erosion) temperature interruption in nutrient flow changes in moisture regime (irrigation) removal of biomass introduction of inorganic nutrients introduction of herbicides, pesticides salinization aquaculture in coastal areas floodplains (accreting systems) cultivation of floodplains fire	soil erosion, loss of capacity to buffer due to there simply being less soil draining of wetlands for cultivation reduces opportunities for sediment trapping and, depending on site-specific circumstances, may actually contribute to sediment loss reduction in P removal, related to sediment loss and dentrification due to loss of anaerobic environments associated with wetland loss the storage of water in impoundments increases opportunity for contaminant degradation/immobilization due to increased opportunities for sedimentation and extended detention periods the loss of floodplains to agriculture as a result of regular flows will reduce their value in terms of sediment accreting and nutrient trapping/release systems water retention–appearance of systems with symptoms of eutrophication is likely to increase as a consequence of nutrient retention, cycling, and internal generation (i.e., C fixation as algae) capacity of drylands to successfully reduce pesticides/herbicides is likely to be compromised by a reduction in area due to conversion to cropping and higher applied loads the risks of salinization both as a result of changes in land use as well as increasing manufacturing and support activities will increase with a further deterioration of dryland systems the increase in aquaculture ponds in drylands in coastal areas will improve the capacity of the system to trap wastes/contaminants, but on the downside this could be to the detriment of people because of bioconcentration/transfer from sediment to harvestable biota
Inland waters	loss of wetlands (cropping) loss of wetlands (irreparable alteration, i.e. reclamation for structures) loss of wetlands water abstraction loss of water changes in land use (e.g., mining) loss of wetlands through modification of hydrology (e.g., high peaks from urban areas, constrictions due to culverts, etc.) abstraction for human use/urban and agriculture storage deterioration due to waste loads deterioration due to increased introduction of waterborne sanitation increase in baseflows salinization	see above for drylands reduction in capacity to detoxify due to direct loss of habitat, increasing loads, and changes in nature of contaminants damming increases capacity to transform wastes, including nutrients, with consequences on water quality; detention times, days to weeks, can lead to eutrophication

(continues over)

Table 15.5. ***continued***

System	Driver of Change	Some Considerations for Detoxification
Coastal	interruption of coastal processes by stabilizing rivers direct loss of habitat (urban/harbor) change in structure (e.g., prawn ponds) deterioration due to waste loads deterioration due to increased introduction of waterborne sanitation increase in baseflows stabilization of flows transportation	see urban increasing nutrient loads, both from local as well as regional origin, may lead to impairment of water quality as the capacity of the system to transform the wasted could be compromised; this is already apparent in the presence of anoxic zones, for example, in the Gulf of Mexico
Marine	reduction in biomass transportation (increase in globalization and trade) dumping accidental spills	increased risk of point source waste load due to increase in global shipping trade increase in nutrient load overriding dilution effect
Forest	changes in land use changes in species composition changes in runoff characteristics changes in water quality (sediment) forest loss acidification fire	see cultivation, inland waters
Mountains	land use changes, deforestation, cropping systems industrial use deforestation, overgrazing, and inappropriate cropping practices lead to irreversible losses of soil and ecosystem function	as above
Polar	land use changes atmospheric composition changes infrastructure development, mining ecotourism	increase in waste loads with temperature being limiting factor limited capacity for microbial degradation due to low temperature
Urban	population expansion increase in impervious surfaces simplification of environments hydrololgy (rapid runoff, contained) nutrient load contaminant types loss of habitat due to direct transformation increase in demand for externally sourced resources, e.g., power, water, food, gas, petroleum waste sludge management	increase in nutrient and other wastes reduced "natural" capacity but potential to replace with engineered systems, constrained by finances and political will, different for industrial and developing countries value systems, immediate survival as opposed to high levels, e.g., aesthetics contaminant types and loads reflect socioeconomic status increased conversion of all other ecosystems, e.g., feedlots, energy provision, landfills, industrial development, to support change in lifestyles

for tissue, especially the fats in tissue, so they tend to accumulate in organisms through bioaccumulation from water or food. As these compounds are not metabolized and are only slowly excreted by mammals and birds, the concentrations of POPs tend to bioamplify, so that organisms at high trophic levels, including humans, are particularly susceptible to detrimental effects.

POP-based pesticides were widely used and are still applied. For example, about 2.6 million tons of DDT were used from 1950 to 1993, while the figure for toxaphene during the same period was 1.33 million tons (Voldner and Li 1995). The remarkable efficacy of this class of insecticides, especially in controlling insect-borne diseases such as malaria, coupled with the intensification of agricultural systems led to their production and wide use. However, use of most of these compounds was curtailed in most countries in the 1970s after their toxicity was demonstrated. While primarily active on nerve conduction chemistry, these substances are acknowledged carcinogens and suspected teratogens, immunotoxins, and hormone disrupters (Guillette et al. 1994; Zahm and Ward 1998; Holladay and Smialowicz 2000; Solomon and Schettler 2000). In many parts of the world, DDT is still used for malaria control and chlordane is still the chemical of choice for termite control. A serious problem facing many developing and transition countries is the issue of stocks and reservoirs of obsolete, discarded, and banned POP pesticides and PCBs. There is an estimated 120,000 tons of obsolete stock of pesticides in Africa (FAO 2001; Tanabe 1988; Goldman and Tran 2002).

Polychlorinated biphenyls have been used mainly in electrical transformers, capacitors, hydraulic fluids, adhesives, plasticizers,

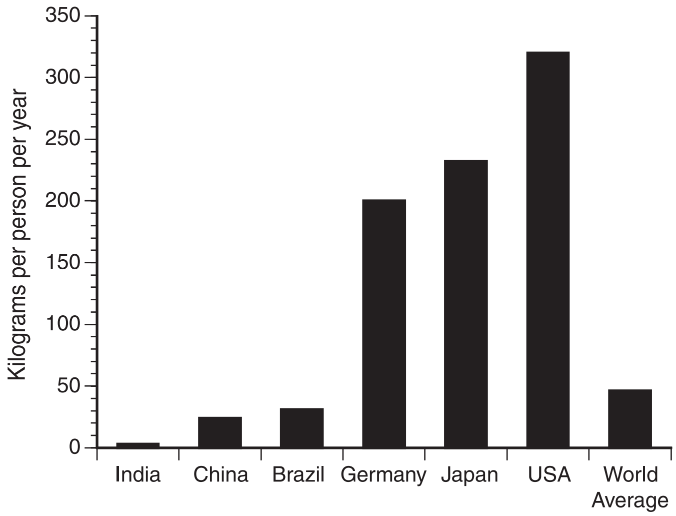

Figure 15.6. Paper Production per Capita in Selected Nations (Brown et al. 1998)

heat transfer fluids, lubricants, cutting oils, and fire-retardants. Global production of PCBs to date has been estimated to be 1.68 million tons (AMAP 2000; UNEP/GEF 2003). PCBs enter the aquatic environment from industrial effluent or urban waste discharges (GESAMP 2001). Dioxins are unintentional products from combustion sources and manufacturing processes such as municipal solid waste incineration, energy production, motor vehicles, smelting, bleaching of paper pulp, and the manufacture of some pesticides and herbicides. Dioxins and the chlorinated furans are also produced naturally during volcano eruption and forest fires (Gullett and Touati 2003).

Volatilization is the principal means of wide dissipation of POPs in the environment. All POPs have a certain vapor pressure or a tendency for the chemical to become a gas and enter the atmosphere. Further, some POPs are initially emitted directly into the atmosphere. POPs may be dispersed over great distances in the air and can now be found anywhere on the globe. They have even reached the polar regions in large quantities through a process called global distillation, where these substances preferentially settle out in the colder air of the polar regions (Wania 2003 and see Chapter 25). POPs also have a strong affinity to associate with particulate matter. In aquatic systems, POPs partition or bind to particles and they sink to bottom sediments, which are their main environmental repository. These legacy POPs can seep back into the water and atmosphere many years or decades after emissions themselves have ceased.

15.7.3 Hydrocarbons

Petroleum hydrocarbons remain the dominant energy source in industrial and most developing countries (UNEP 1994), and yet they are associated with a range of environmental issues. The devastating effects on marine organisms of large oil spills from shipping, oil exploration, and production, for example, are well known (NRC 2003). Management of spilled oil in waters has largely been by attempts to contain and recover oil through use of booms and mechanical skimming and reprocessing of the oil recovered. Unfortunately, in large oil spills most is not recoverable. Unrecovered oil eventually decays in the environment due to microbial degradation, but different fractions of petroleum hydrocarbons are degraded at different rates. The lighter fractions can be degraded relatively rapidly, typically within days to weeks in temperate conditions, except where they are mixed into sediments or soils where there is no oxygen (as described earlier). The heavier fractions are very persistent, requiring weeks to months to be degraded, even under conditions with sufficient oxygen. Hydrocarbons that get mixed into soils and sediments where there is little oxygen persist for years to decades.

One sub-group of hydrocarbons that can cause significant problems are the polycyclic aromatic hydrocarbons. The primary environmental source of these is a residue of combustion processes, though they are also found to some extent in petroleum oils. PAHs—both the parent compounds and alkylated homologues—are carcinogens (and mutagens and teratogens), and though subject to microbial degradation, they are the most environmentally persistent of the hydrocarbons. PAHs emitted into the atmosphere will deposit on land in dry and wet deposition and may accumulate in aquatic sediments through scavenging (GESAMP 2001).

Recent studies have established that land-based sources are the major input of hydrocarbons into the marine environment (GESAMP 2001). The major land-based sources identified are urban runoff, refinery effluents, municipal wastes, and used lubricating oils. Used lubricating oils are often contaminated with metals and high concentrations of PAHs, which makes them particularly hazardous. Pathways through which used oil get into surface water sources include oil dumped down drains that discharges into surface waters and oil poured on the ground and washed into groundwater or surface water.

15.7.4 Salinization

Salinization is a process resulting in an increasing concentration of salts in soils, water, or both. A number of activities can be linked to increases in the salt concentration of surface waters and soils. These include soil disturbance by activities that expose the soil and subsoil to weathering processes and subsequent leaching of salts the nature of which are determined by the composition of the parent material; the use of water for flushing human and industrial wastes; water recycling; water losses due to evaporation or evapotranspiration, such as in irrigation systems; discharge of saline groundwater; and changes in land cover, such as the replacement of trees with grasses, permitting already saline groundwaters to approach the surface due to a reduction in evapotranspiration by deep-rooted trees.

An example of the effects of changes in land use is shown in Figure 15.7, which illustrates increasing conductivity and sulfate concentrations (measures of salinity) in response to open cast (strip) mining in one of the principal coal mining areas in South Africa. The strip mining exposes the soil and subsoil profiles to weathering processes, resulting in the dissolution of minerals, in particular pyrite.

Salts do not degrade, and their concentrations can only be influenced by dilution through the use of sufficient water to move them to where they have less influence—in the ocean, for example. When water with even a low salt content is added continuously to an ecosystem, and when the water is allowed to evaporate or be lost through plant evapotranspiration, the salt remains and accumulates. For example, irrigation water with a salt content of 0.3 grams per liter applied at a rate of 10,000 cubic meters per hectare per year transfers 3,000 kilograms of salt per hectare per year into the soil (Oosterbaan 2003; see also Chapter 22).

Salinization of agricultural soils affects plant growth by restricting the uptake of water by the roots through their high osmotic pressures and by interfering with a balanced absorption of

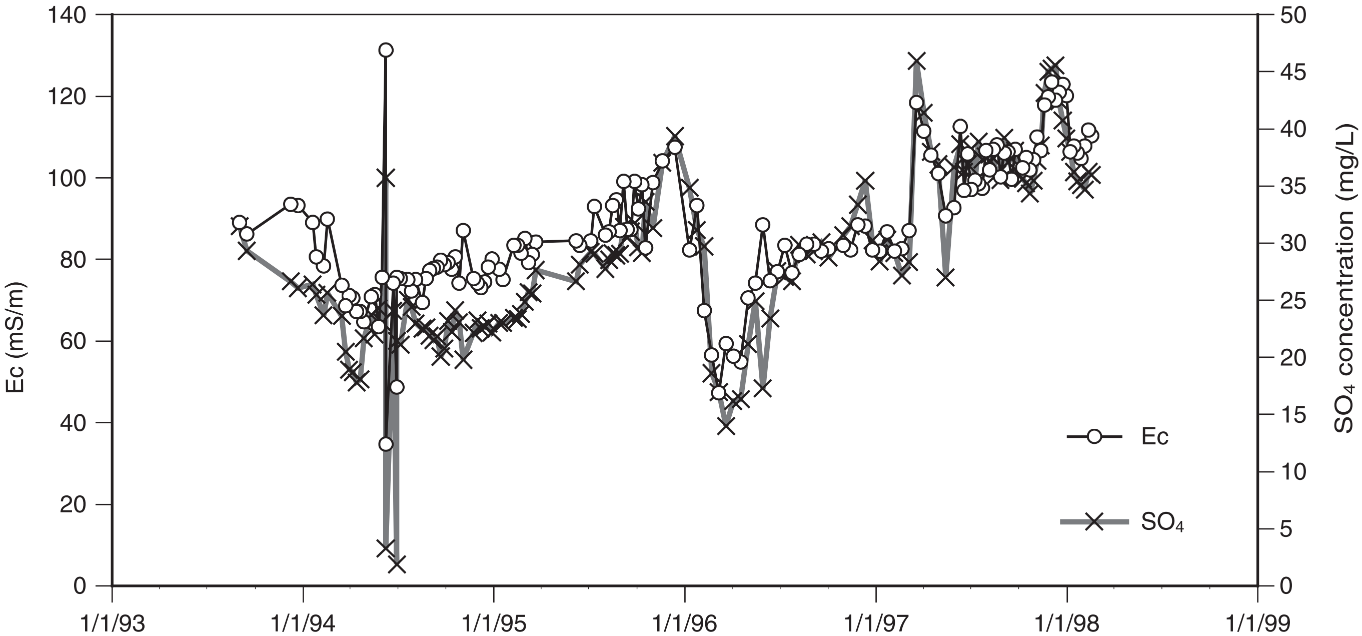

Figure 15.7. Salinization in the Olifant River, South Africa, 1993–98. Changes in electrical conductivity and sulphates measured in the Olifant River showing decreasing quality, attributed largely to coal mining activities. The Ec is a measure of the salt in the water. (S. African Dept. of Water Affairs and Forestry 1999 gauging station B3H017Q01)

essential nutritional ions by the plants. Different plants have different levels of sensitivity, so salinization can cause a shift in local plant communities.

These processes can have local economic consequences. A study on the effects of salinity changes in an irrigation area associated with the Vaal River in South Africa suggested that income of a specific group of farmers could be reduced by up to 84% as a result of crop changes and reductions in yields (Du Preez et al 2000; Viljoen and Armour 2002).

Estimates of the extent of salinization in the world run in the hundreds of millions of hectares, primarily in the more arid regions (Brinckman 1983; see also Chapter 22). The costs of salinization are high, with an estimate provided by the Australian Museum of AUS$500 million a year in Victoria alone (AM 2003).

The economic impact of salinization of surface waters runs beyond agriculture alone; Table 15.6 provides an example of the costs of increasing salinity on various sectors of society in a South African case study (Urban Econ 2000). The costs and factors considered for the identified sectors include:

- *in households*: maintenance costs (water heaters and plumbing), accelerated replacement costs, costs of soaps and detergents as well as the current anticipated salinity level;
- *in agriculture*: cost of water supply, maintenance costs, plant, chemicals;
- *in mining*: evaporative cooling circuits, service water circuits, metallurgical plant circuits, flotation circuits, electrolytic processes, irrigation water circuits, probabilistic distribution of management behavior, cost of water supply, cost of chemicals, cost of water treatment, cost of discharge, costs of scaling, salinity ratio;
- *in industry*: cost of water supply, maintenance costs, cost of chemicals, cost of plant replacement, current anticipated salinity, salinity threshold where expenditure patterns change; and
- *in water services*: cost of water supply, maintenance costs, chemical costs, plant replacement costs, current or anticipated salinity, salinity threshold where expenditure patterns change.

The greatest direct cost implications occur at the household sector, attributed to the fact that this constitutes the largest group of treated water users in the economy, compared with sectors that use predominantly untreated water.

With increasing pressure on surface waters, particularly in arid areas, there is likely to be an increase in the demand for water recycling and reuse (IWA 2004). This will undoubtedly lead to an increase in salinization of water, with associated consequences for downstream users.

15.7.5 Wetlands: Natural Defense Mechanism for Pollution Abatement

Depending on their type, wetlands can improve water quality, provide flood control, provide habitat for young of commercially valuable fish, provide habitat for many types of wildlife, help prevent erosion, and help reduce waterborne disease (see Chapters 7, 14, 19, and 20). Wetlands represent one of the major mechanisms to treat and detoxify a variety of waste products, and there have been many efforts to construct artificial wetlands to obtain these wetland functions.

15.7.5.1 Wetland Processes

One of the key functions that wetlands perform is to reduce concentrations of nitrogen in water. The close proximity of aerobic and anaerobic conditions often found in wetlands create a suitable environment for denitrification to take place. Denitrification converts nitrate, readily used by plants, to nitrogen gas, generally unavailable to plants, thereby reducing eutrophication (as described in the next section). Some wetlands have been found to reduce the concentration of nitrate by 90%, and artificially constructed wetlands have been developed specifically to treat nitrogen-rich sewage effluents.

Wetlands also act as a filter or trap for many waterborne wastes, including metals, organic chemicals, and pathogens. Metals and many organic compounds are adsorbed to the sediments

Table 15.6. Summarized Direct Costs of Salinity Changes on Selected Economic Sectors in South Africa, 1995. Negative values indicate no additional costs due to salinization. The percentages represent the increase in total operating costs due to salinization. For example, the net costs of mining were estimated to increase by 3.17% at 600 milligrams per liter. (Urban Econ 2000)

Sector	Salinity (mg/l TDS) 200	400	600	800	1,000	1,200	Contribution at 600 mg/l
	(milligrams per liter)						(percent)
Mining	–7.309	–2.212	0.844	4.863	10.209	17.816	3.17
Business and services	–1.843	0.487	1.211	1.707	2.209	2.697	4.55
Manufacturing 1	–0.145	0.028	0.086	0.123	0.160	0.198	0.32
Manufacturing 2	–2.825	0.294	1.351	1.993	2.635	3.278	5.07
Agriculture	0.000	0.000	0.439	0.439	0.427	0.503	1.65
Households (suburban)	–35.12	–11.71	11.70	35.12	58.53	81.95	43.94
Households (townships)	–27.93	–9.309	9.309	27.93	46.54	65.16	34.94
Households (informal)	–5.081	–1.694	1.694	5.081	8.469	11.85	6.36
Total	**–80.25**	**–24.11**	**26.64**	**77.25**	**129.22**	**183.46**	**100.00**

in the wetlands, and the relatively slow passage of water through many wetlands provides time for pathogens to lose their viability or be consumed by other organisms in the ecosystem. For easily degraded chemicals, their adsorption to sediments and slow passage through wetlands provides time for their degradation. However, for metals and persistent organic chemicals, wetlands become permanent traps, as these wastes either do not degrade or degrade very slowly. Many metals are held in sediments by precipitation with sulfides or as surface oxides (Barnes et al 1991).

Although metals and persistent organic chemicals can build up to high enough concentrations to have detrimental effects on the wetland functions (for example, the impairment of denitrification by metals (Slater and Capone 1984)), moderate waste loadings can generally be tolerated by wetlands without loss of services. Moderate loadings of plant nutrients lead to enrichment (analogous to fertilization of crops or lawns), while severe loadings will lead to a major loss in wetland productivity, structure, and function through eutrophication. Unfortunately, the threshold between where loadings are tolerated and where they will do damage to wetlands is not easily determined and depends on the specific conditions in each wetland.

15.7.5.2 Wetlands and Human Activities

The impact of human activities on wetlands has been drastic, and it is speculated that some 50% of world wetlands have been lost (see Chapter 20), with the greatest changes occurring in industrial countries in the first half of the twentieth century (BEST 2001). Wetlands have been drained for agricultural purposes or filled to create lands suitable for construction. Quite often wetlands have also been used as the end point of wastewater effluent, receiving large volumes of industrial, municipal, and agricultural wastewater. The impact of these effluents on the quality, density, and structure of living communities is substantial, as indicated by diversity indices (Patric 1976; Stevenson 1984). Wastewater effluent can significantly affect phytoplankton species diversity and community structure (Sullivan 1984; Gab Allah 2001), thereby reducing the wetland's capacity to detoxify wastes and to re-oxygenate water. The impairment of wetlands' ability to detoxify of wastes is affecting the quality of groundwater particularly, for example, in northeastern Egypt (Gab Allah 2001), where elevated levels of salinity and high concentrations of heavy metals in groundwater are reported.

15.7.6 Eutrophication

The addition of nitrogen or phosphorus (both essential, and often limiting, in plant growth) can have very undesirable effects on freshwater and marine systems (see Chapters 19 and 20). In freshwater systems, phosphorus is usually in shortest supply. Additions of phosphorus can stimulate large blooms of algal types usually not found in abundance. In some cases, dense filamentous algal mats form, altering the environment to the exclusion of other species and reducing biodiversity. The increased levels of algae sink to the bottom and are broken down by bacteria and other organisms. This decay of the plant material takes up oxygen from the water, and with the decay of enough plant material, the bottom water can become anoxic. The link between phosphorus additions and the undesirable effects on lakes and rivers has been clearly established through both direct experimentation with whole lakes (Schindler et al. 1971; Schindler 1973) and through cross-lake comparisons (Vollenweider 1976).

In coastal and marine systems, nitrogen is usually the limiting nutrient. Additions of any of the various forms of reactive nitrogen usually stimulate plant growth. Reactive nitrogen is nitrogen in the forms of nitrate, nitrite, ammonia, or organic nitrogen that is readily biologically available. Nitrogen gas (N_2 or di-nitrogen), which constitutes 79% of the atmosphere, cannot be used by most plant species. Figure 15.8 shows how the rate of plant production in several coastal marine ecosystems is very strongly influenced by the input of reactive nitrogen nutrients.

As with lakes, the increase in plant material, when settled to the bottom of a bay or estuary, can lead to loss of oxygen and the exclusion of all higher organisms, including the fish, clams, crabs, shrimp, and other valuable harvestable seafood. Eutrophication of coastal waters often stimulates microscopic forms of algae (phytoplankton), which in turn causes a decrease in light penetration to areas that would normally support seagrass beds, an environment that provides a valuable nursery for many desirable species. There is no simple relationship between N loading rates and effects, because the effects depend on the depth, circulation, temperatures, and other characteristics of each system.

Eutrophication in coastal waters has also been linked to the increased prevalence of large blooms of toxic phytoplankton, or red tides (see Chapter 19). The toxins in red tide species may be accumulated in marine organisms and cause significant toxicity to

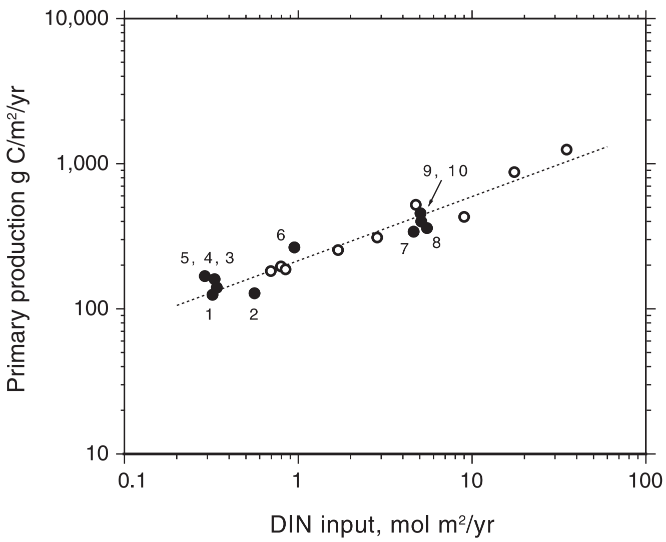

Figure 15.8. Marine Plant Production and Nitrogen Loadings. The increase in phytoplankton production by increased dissolved inorganic nitrogen inputs. Open circles are data from the MEL Marine enclosures. Numbered systems are: 1. Scotian Shelf; 2. Sargasso Sea; 3. North Sea; 4. Baltic Sea; 5. N. Central Pacific; 6. Tomales Bay; 7. Continental Shelf, New York; 8. Outer-Southeast U.S. Continental Shelf; 9. Peru Upwelling; 10. Georges Bank. (Nixon and Pilson 1983)

humans. It should also be noted that some nuisance algal species are not correlated with eutrophication (for examples, see Keller and Rice 1989; Gobler and Sanudo-Wilhelmy 2001; Gobler et al. 2002).

The amount of fixed nitrogen and phosphorus cycling through ecosystems has been greatly increased by human activities (see Chapter 12). Phosphorus is usually mined from mineral deposits. A major source of nitrogen is an industrial process (the Haber process) that converts nitrogen gas from the atmosphere into ammonia. The vast majority of nitrogen fertilizers in use today are from this process. Reactive nitrogen is also generated during combustion processes in industrial, heating, and automotive combustion. Combustion sources produce enough reactive nitrogen in areas of high activity, such as Western Europe and the eastern United States, to elevate atmospheric concentrations of reactive nitrogen to up to 10 times natural concentrations.

The combination of synthetic nitrogen in agricultural fertilizers, nitrogen-rich human sewage inputs, and deposition of atmospheric reactive nitrogen to watersheds has raised the global average river concentrations of nitrogen to five times preindustrial levels, and rivers in heavily populated areas and industrialized areas have nitrogen concentrations some 25 times higher than natural levels (Meybeck 1982). The delivery of this nitrogen to coastal waters has, on a global average, doubled nitrogen concentrations in coastal waters, certainly one of the largest chemical alterations of Earth's ecosystems. The relative importance of the agricultural, combustion, and sewage inputs of nitrogen varies between different watersheds (Hinga et al. 1991), with all three sources being important in some systems. Management of nitrogen eutrophication may require addressing all three sources.

Low levels of eutrophication probably do not adversely affect aquatic ecosystems or impair human well-being. Indeed, as in agricultural systems, fertilization of coastal systems may lead to greater harvests of seafood (Nixon 2003). However, the very large loadings of fertilizers that occur with intense agricultural and industrial activity and dense human population (especially in the coastal zone) have pushed many aquatic systems into conditions that exceed the capability of the system to adsorb the nutrients without detrimental effects. These systems are marked with anoxic conditions and the loss of biodiversity (including coral reefs) and harvestable species. (See Chapters 19 and 20.)

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