

CHAPTER 16

SOIL AND LAND POLLUTION

J.F. Artiola, J.L. Walworth, S.A. Musil and M.A. Crimmins



Irrigation wheels in Southwest U.S. *Photo courtesy J.F. Artiola.*

16.1 INTRODUCTION

Mining, agriculture, and deforestation are important energy-intensive activities that impact economies and at the same time directly and indirectly cause soil and land pollution. Mining produces vast quantities of almost sterile and structureless geologic materials, such as crushed rock that often contain significant amounts of toxic metals, such as lead and cadmium, and salts. Mine overburden and tailings are often stockpiled next to large open pit excavations. Modern agricultural production requires the use of large quantities of commercial fertilizers and pesticides, and produces animal wastes, all of which can pollute land and water. Land deforestation indirectly affects the quality of land and water by increasing the rates of soil erosion and sediment transport, and accelerating the loss of the nutrient-rich soil surface. Invasive exotic plant species also have a significant impact on the quality of our lands by creating soil conditions that may be toxic to other plants and by increasing fire hazards. All of these activities in turn can affect soil salinity and acidity of surrounding land areas by releasing or concentrating unwanted metals, salts, and acid or acid-forming minerals. These materials can also be released into air or water sources.

Because these activities have played a traditional key role in the growth and development of our modern society, to date their impacts on the environment have not been closely monitored or regulated. It is important to recognize the impacts that these activities have on our environment and there is a need to achieve a balance between their social benefits and the need for the preservation of our environment. The restoration of land adversely affected by these activities is discussed in Chapter 20.

16.2 SURFACE MINING

Mining of coal and metal ores was one of the earliest contributors to the industrial revolution. When transformed, these ores became both the fuel and the building blocks of

industrialization. Although carbon-based plastic materials, together with such organic chemicals as pesticides and solvents, have dominated industrial production since the early 1950s, metal-based goods remain fundamental to modern industry. Numerous modern goods—from cars to paints—require the use of such common metals as iron, aluminum, and copper. In addition to these three metals, other less common metals and metalloids, such as lead, cadmium, nickel, mercury, arsenic, and selenium, are essential for the manufacture of these and other goods. Metallic elements are therefore commonly found in industrial wastes, where they have complex and still poorly understood effects on the environment. What is known is that uncontrolled and concentrated releases of metals into the environment present both short- and long-term hazards to human health and adversely affect the environment.

Industries that mine and process ores, drill for oil and gas, and/or burn coal also generate large volumes of salt-containing wastes. For these industries, the predominant chemical species include sodium (Na^+), calcium (Ca^{++}), sulfate (SO_4^{--}), and chloride (Cl^-), and carbonate (CO_3^{--}) ions, which are also very abundant in the natural environment. Because these wastes are not intrinsically hazardous or acutely toxic, they do not pose an immediate risk to health and the environment. Nonetheless, the volumes of these wastes that are generated each year are massive enough to be of concern.

16.2.1 Mine Tailings

Mining activities and, in particular, strip mining of metal ores produce vast quantities of residues called **mine spoils** and **mine tailings** that may contain significant concentrations of metals (Figure 16.1). Mine spoils or **overburden** consist of surface materials that do not contain the metal of interest and that are therefore stockpiled at the surface, often resembling large “mesas.” Mine tailings, in contrast, are the crushed mineral rock that has been processed to release the metal of interest. These are often pumped as a slurry in “lifts” of 3-m dimension into valleys or depressions. Mine tailings can be 35

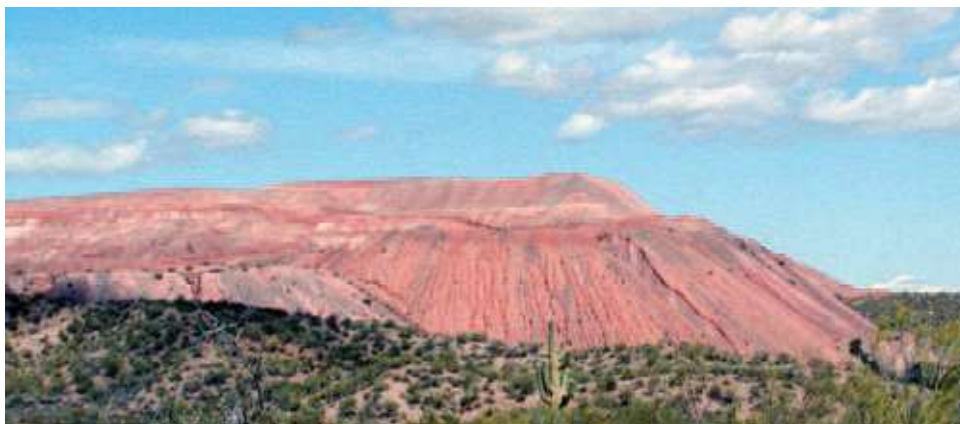
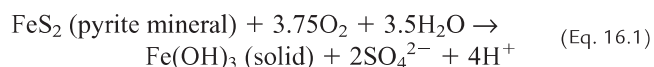


Figure 16.1 Copper mine tailings and spoils in Southwest U.S. Photo courtesy J.F. Artiola.



Figure 16.2 Acid mine drainage from gold mine in South Dakota. From U.S. Fish and Wildlife Service.

m deep due to successive depositions of lifts (see also Chapter 20). Thus, these residues, which are usually composed of unweathered primary minerals, can alter the environment physically and chemically. Strip mining for copper, for example, produces large quantities of tailings that often contain concentrations of 100–10,000 mg kg⁻¹ of such metals as cadmium and lead. Similarly, iron pyrites (FeS₂), which are often associated with copper, silver, and lead ores, can have a devastating impact on the aquatic environment because their oxidation releases sulfuric acid into the environment (Figure 16.2). The overall reaction is described as follows:



In an acid stream (pH <3), fresh pyrite can react in a cascading effect with soluble ferric iron (Fe³⁺), creating even more acidity (Stumm and Morgan, 1996). The reaction rate is controlled by the oxidation of Fe²⁺ to Fe³⁺ in the presence of O₂, and results in lowering the pH of the environment. This process can also occur biologically via autotrophic bacteria which thrive at pH 2–3 (see Chapter 5).

Mining operations that treat or leach ores and/or store acid chemicals for the extraction of metals can generate large volumes of acidic metal-containing wastewaters and/or leachates. For example, low-grade Cu ore is often extracted by means of sulfuric acid heap leaching. In this process, crushed Cu ore is continuously leached with sulfuric acid until most of the Cu is solubilized due to both the high acidity and formation of Cu-sulfate complexes. Spent acid solutions, usually contaminated with other metals, must be neutralized and stored in lagoons or impoundments. Gold mining also produces vast quantities of spent ores and liquid process streams that usually contain residual levels of cyanide (CN⁻) complexes. Metal-cyanide complexes are usually either stable in the soil environment or biologically degraded into nontoxic forms of N (see Chapter 5). However, when released into aquatic systems, these residues can be extremely toxic to fish if free cyanide is released into the water.

16.2.2 Air Emissions

Metal smelting and refining processes generate wastes that may contain multiple hazardous metals, such as lead, zinc, nickel, copper, cadmium, chromium, mercury, selenium, arsenic, and cobalt. These elements may be found in the ores used or they may be added as mixed metals into the melts to produce metal alloys. Thus, metal-containing smelter wastes have to be treated and disposed of as hazardous wastes. Smelting and refining require very high temperatures to reduce the metal ores (such as pyrite and bauxite for iron and aluminum production) into pure metal and to refine metals and alloys. For example, iron melts at 1536°C, copper melts at 1083°C, and aluminum melts at 660°C. At these temperatures, many other metals and metal compounds volatilize; for example, the boiling points of mercury, cadmium, zinc, and arsenic are 357°C, 765°C, 906°C, and 613°C, respectively. Therefore, smelter and metal refining stacks that do not have gas scrubbers can release significant amounts of relatively volatile toxic metals into the atmosphere that eventually deposit onto the land.

16.3 DEFORESTATION

Deforestation is simply the conversion of forested tracts to barren lands. This is usually done by clear-cutting trees and removing the wood (Figure 16.3). Forested areas are typically cleared to make room for agricultural operations or to harvest wood as a fuel source or for lumber products. Much of the deforestation occurring globally is due to slash-and-burn operations that make room for agricultural operations.

The process of deforestation results in many undesirable environmental impacts at multiple scales. Local impacts include decreasing soil stability, increasing erosion and sediment transport into streams, reduction in biodiversity through loss of habitat (see Chapter 24), and alterations to microclimates that typically increase local temperatures because of loss of vegetation and increased numbers of heat islands (see also Chapter 21). Degradation of air quality is often at the regional scale if deforestation is being driven by



Figure 16.3 Example of deforested area with downed slash in foreground. United Nations Environmental Program.

burning down slash. This promotes episodes of high levels of atmospheric particulate matter and carbon monoxide gas that are harmful to the health of both humans and wildlife (see also Chapter 24). Deforestation can also produce impacts on a global scale. Research over the past decade has shown that the cutting and burning of large forest tracts is quickly liberating large amounts of carbon and increasing levels of the greenhouse gas, carbon dioxide, in the atmosphere (Zhang et al., 2003). Removing forest vegetation further disrupts the global carbon balance by eliminating the living trees that served as a sink for carbon dioxide. Photosynthesis in trees converts atmospheric carbon dioxide into plant cellulose, drawing carbon out of the atmosphere and storing it as biomass (see also Chapter 24).

16.3.1 Local Land Pollution Impacts of Deforestation

Removal of forest vegetation increases the potential of soils to become eroded by wind and/or rainfall. Runoff during precipitation events can promote both the erosion of soils and the transport of sediments into river systems. These sediments will degrade water quality by increasing turbidity and levels of dissolved nutrients (*e.g.*, phosphorus and nitrates) (see also Chapter 18). Experiments to document the effects of deforestation on watershed dynamics and stream water quality have been conducted in several experimental watersheds throughout the U.S. Results from the Hubbard Brook Experimental Forest in New Hampshire show large increases in dissolved nutrient levels and sediment loads in-stream for a deforested watershed area, as compared to a control forested area watershed (Bormann and Likens, 1979; Bonan, 2002).

A more serious form of land-based pollution has been tied to deforestation in areas of South America. High-levels of mercury have been found in the blood of people in many rural communities in Brazil where fish is a staple food. The high mercury levels were initially attributed to gold mining operations found throughout these areas. Further study has shown that naturally occurring pools of mercury found in soil and organic matter were being readily transported into streams through runoff following deforestation (Veiga et al., 1994). The removal of forest vegetation allowed mercury that was initially stabilized in soil organic matter to become mobile and be transported into streams.

16.3.2 Regional Air Quality Impacts of Deforestation

Deforestation is often accompanied by the burning of biomass. Sometimes the burning is done to clear slashed vegetation, and at other times harvested forest vegetation is burned as a fuel source for heating and cooking. In either case, the burning of forest biomass on large scales can cause serious air quality problems. Particulate matter, ozone, and carbon monoxide are all produced when forest biomass is burned, and all pose health risks to humans (see also Chapters 3 and 23). Figure 16.4 shows the impact of large-scale forest

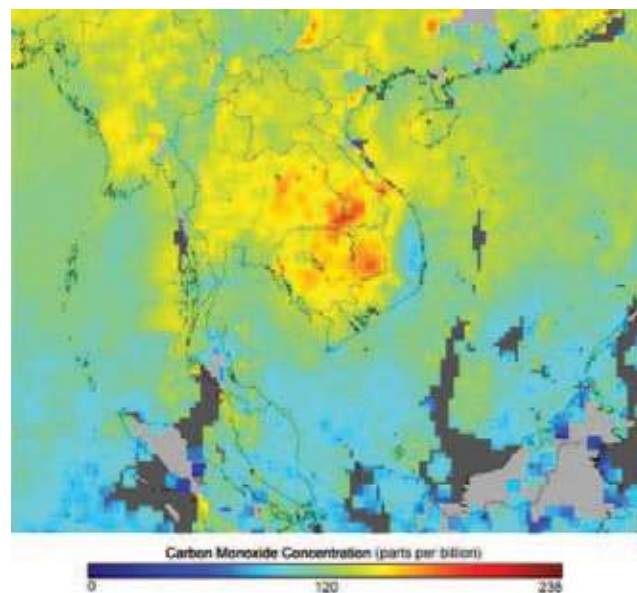


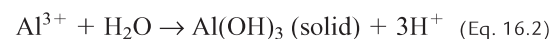
Figure 16.4 Atmospheric carbon monoxide concentrations over Asia estimated using data collected by the NASA Terra satellite. From NASA.

biomass burning for heating and cooking on atmospheric carbon dioxide levels across Asia (Heald et al., 2003).

16.4 SOIL ACIDITY—SALINITY

16.4.1 Acid Soils

Acid soils occur naturally or develop as the result of continuous additions of acid-forming fertilizers. Natural acid soils are usually found in the tropics, the result of thousands of years of excessive weathering of soil minerals. High rainfall and year-around high temperatures leaches all basic cations (such as Na, Ca, Mg, and K) and pH buffering minerals (such as carbonates). Also, this climate promotes the transformation and subsequent leaching of Si from Si-based minerals, leaving acidic iron and aluminum oxides minerals. For example, soluble aluminum can release protons into the soil environment by the following general reaction:



Similarly, the presence of pyrite minerals in some soils can lead to the formation of acidic soil conditions, in a reaction similar to Equation 16.2 above.

Agricultural soils can also become acidic due to the continuous additions of large amounts of acid-forming fertilizers such as ammonia and urea. For example, one mole-equivalent weight of ammonium (NH_4^+) can produce two mole-equivalent of H^+ after it is fully oxidized to nitrate (NO_3^-) in the soil environment.

Other sources of acid-forming chemicals that impact the soil environment include coal-burning air emissions (SO_2 , NO_x) that are hydrolyzed and scrubbed out of the atmosphere by rain (see also Chapter 20).

TABLE 16.1 Soil salinity rankings.

PARAMETER (mS cm ⁻¹)	NON- SALINE	SLIGHTLY SALINE	MODERATELY SALINE	SALINE
EC*	<4	4–8	8–16	>16

*Measured on a water-saturated soil paste extract (USDA, 1954).

16.4.2 Salinity

Soil salinity is a measure of the minerals and salts that can be dissolved in water. In most cases, the following mineral ions are found in soil-water extract listed in order of importance:



Increased soil salinity has progressive and often profound effects on the structure, microbial diversity, and plant activity of soils. Soil salinity is measured by using electrical conductivity (EC) measurements of a water-saturated soil paste extract (Table 16.1).

An excessive concentration of Na ions in soils produces an imbalance in the ratio of monovalent cations to divalent cations. This is measured by the exchangeable sodium percent (ESP). Salt-affected soils are thus also classified by their ESP as shown Table 16.2 (see also Chapter 20).

There are numerous sources of soil salinity. Natural soil salinity occurs in hot arid and semi-arid climates with ≤ 27 cm of annual rainfall. Soils and lands that have shallow water tables can develop saline soils due to excessive water evaporation and the concentration of salts. Poor water quality and irrigation practices also contribute to the salinization of thousands of acres of farmland each year around the world. Salt-affected soils occupy, on a global basis, 952.2 million ha of land. These soils constitute nearly 7% of the total land area or nearly 33% of the potential agricultural land area of the world (Gupta and Abrol, 1990).

16.5 SOIL EROSION

Soil particles can act as carriers of other contaminants that are sorbed to particulate surfaces. For example, phosphorus is often associated with soil particles and sediments. When soil particles are eroded and discharged into an aquatic environment, the resulting sediments increase the P nutrient levels of the water and can cause excessive growth of algae and other aquatic plants. This process, together the concomitant reduction in oxygen, is known as eutrophication (see also Chapter 18).

Organic chemicals, including herbicides, insecticides, fuels, solvents, preservatives, and other industrial and

agricultural chemicals, can be similarly adsorbed and desorbed from waterborne soil particulates.

Naturally occurring particulate contaminants come from many sources, including agricultural operations, logging, construction-related activities, mining and quarrying, and unpaved roads, and from wind erosion (see Chapter 9). Soil erosion is a natural process that occurs continuously, but is often accelerated by human activities. Several factors are required for soil material to become dislodged and transported into air or water. Soil must be susceptible to erosional processes, which generally requires that the soil be exposed to erosional forces. In the first phase of soil erosion, soil particles become dislodged. Energy inputs must be adequate to dislodge particles. In the second phase, the particles are transported. Various soil properties, which we will examine, determine the susceptibility of soil particles to dislodgement.

16.5.1 Soil Water Erosion and Control

We will first consider particle movement caused by water. As indicated in Chapter 2, soil particles are usually formed into aggregates, which vary considerably in size, shape, and stability. Organic and inorganic materials and certain soil cations are the primary aggregating and inter-particle cementing agents. In the detachment phase, individual particles are dispersed or separated from aggregates or cemented particles. The source of the energy responsible for detaching soil particles is either raindrop impact or the flow of runoff water. When raindrops, which travel at approximately 900 cm s⁻¹, hit bare soil, the kinetic energy of the raindrops is transferred to the soil particles, breaking apart aggregates and dislodging particles. Dislodged particles can be moved over 1 m in the splash from raindrop impact. They are moved larger distances by runoff water, which can dislodge additional particles through scouring action. Smaller particles are transported more easily than large ones, and faster flowing water can carry a heavier particulate load than slow-moving water. When uniform shallow layers of soil are eroded off areas of land, this is called **sheet erosion**. Directed water flow cuts channels into the soil. Small channels are called **rills**; large channels are **gullies** (Figure 16.5).

The process of water erosion has been described by the **United States Department of Agriculture (USDA) Universal Soil Loss Equation (USLE)**, later modified to the **Revised Universal Soil Loss Equation (RUSLE)**.

$$A = 2.24R \times K \times LS \times C \times P \quad (\text{Eq. 16.3})$$

where:

A = the estimated average annual soil loss (metric tons/hectare)

TABLE 16.2 Soil exchangeable sodium percentage rankings.

PARAMETER	ADEQUATE	BORDER-LINE	INADEQUATE**	COMMENTS
ESP*	<10	10–15	>15	Sandy soils may tolerate ESP values up to 15

*ESP calculated using a mol-equivalent units, using the concentrations of Na⁺, Ca⁺⁺, Mg⁺⁺, and K⁺ soil water extractable or exchangeable ions.

**Considered a sodic soil (USDA, 1954).



Figure 16.5 Soil erosion in abandoned farmland in southern Arizona that results in a gully. Photo courtesy J.F. Artiola.

R = the rainfall and runoff erosivity index. This describes intensity and duration of rainfall in a given geographical area. It is the product of the kinetic energy of raindrops and the maximum 30-minute intensity.

K = the soil erodibility factor. K is related to soil physical and chemical properties that determine how easily soil particles can be dislodged. It is related to soil texture, aggregate stability, and soil permeability or ability to absorb water. It ranges from 1 (very easily eroded) to 0.01 (very stable soil).

LS = a dimensionless topography factor determined by length and steepness of a slope. The LS factor is related to the velocity of runoff water. Water moves faster on a steep slope than a more level one, and it picks up speed as it moves down a slope. Therefore, the steeper and longer the slope, the faster runoff water will flow. The faster water flows, the more kinetic energy it can impart to the soil surface (kinetic energy = mass \times velocity²).

C = the cover and management factor. Cover of any kind can help protect the soil surface from raindrop impact and can force runoff water to take a longer, more tortuous path as it moves down-slope, slowing the water and reducing its kinetic energy.

P = the factor for supporting practices. This factor takes into account specific erosion control measures. Erosion control practices reduce the P factor.

In the past few decades, farmers have tried to reduce tillage that leaves soil bare and to minimize the amount of time that the soil surface is exposed to raindrops. These new agricultural practices are collectively known as **Reduced Tillage** or **Minimum Tillage** systems (see Figure 16.6). On highly erodible lands, specific erosion control practices include contour planting strip cropping or terracing, all of which can effectively reduce erosion.

Bare soil at construction sites and along road cuts is often covered with synthetic fabrics called geotextiles. These coarse woven materials provide immediate protection and may be used in conjunction with seeding of cover crops that can provide long-term cover. Grass or other plants can be seeded with a hydroseeder that sprays a mixture of seed, fertilizer, mulch, and polymers that cement the mixture into a cohesive soil covering that gives temporary protection to the soil surface until the seeds can germinate and plants cover the soil.



Figure 16.6 No-till cotton planted into crop residue to protect the soil surface. From USDA, image number K8550-8. From *Environmental Monitoring and Characterization* © 2004, Elsevier Academic Press, San Diego, CA.



Figure 16.7 A rock-filled dam erosion control structure. From *Environmental Monitoring and Characterization* © 2004, Elsevier Academic Press, San Diego, CA.

Permeable barriers made of straw bales or woven fabrics can be used to slow water and reduce its ability to carry sediments. Runoff water can be trapped in settling ponds in which water velocity is eliminated or greatly reduced, allowing suspended particles to settle out, and reducing sediment loads before overflow water is released. If suspended colloids are in a dispersed condition, flocculating agents may be added to aggregate particles into larger assemblages that rapidly settle out of suspension. **Gabions** or wire mesh containers filled with rocks can also be used to control water erosion (Figure 16.7).

16.5.2 Soil Wind Erosion and Control

Like water erosion, wind erosion has two phases: detachment and movement. As the wind blows, soil particles are dislodged and begin to roll or bounce along the soil surface in a process called **saltation**. Larger soil particles can move relatively short distances in this way, but, more importantly, as the large particles bounce and strike smaller particles and aggregates, they provide the energy necessary to break aggregates apart and suspend smaller particles in the air. Smaller particles remain suspended in air for longer periods of time and are therefore more likely to travel much longer distances. As in the case of water erosion, models that examine the factors important in wind erosion are useful in predicting wind erosion (Saxton et al., 2000).

It should be noted that finer textured soils (those with more silt and clay sized particles) are less erodible than sandy soils. This reflects the ability of soil aggregates to hold the soil in place during high wind events. On the other hand, PM_{10} consists largely of silt-sized particles, and $PM_{2.5}$ is mainly clay. Therefore, soil wind erosion and particulate matter production are not directly related (see also Chapter 6).

Wind velocity, a major factor in soil wind erosion, can be decreased with windbreaks. These may be living windbreaks of planted trees, shrubs, or grasses, or they can be constructed material such as fences or screens. Windbreaks are

most effective when placed perpendicular to the direction of the prevailing wind. Effects of windbreaks extend to as much as 40 to 50 times the height of the windbreak; however, the area adequately protected by the windbreak is usually smaller. Effective control is usually considered to extend to about 10 times the height of the windbreak. Wind erosion is reduced by a rough soil surface.

Surface roughness can be controlled by creating ridges or a rough surface with tillage implements. Ridges 5 to 10 cm in height are most effective for controlling wind erosion. Soil surface can also be protected by providing vegetative or other surface cover, such as straw, hay, animal manure, or biosolids. The soil water erosion control measures discussed earlier also provide effective wind erosion control.

Various amendments that bind soil particles together, including calcium chloride ($CaCl_2$), soybean feedstock processing byproducts, calcium lignosulfate, polyvinyl acrylic polymer emulsion, polyacrylamide, and emulsified petroleum resin are applied to unpaved roads to reduce particulate emissions. Unpaved roads can also be covered in gravel or similar nonerodible surfacing materials. However, most of these treatments generally offer only temporary dust control and must be periodically repeated.

16.6 AGRICULTURAL ACTIVITIES

16.6.1 Fertilizers

Plants need numerous chemicals in order to complete their life cycles. There are at least 16 **essential elements** required for the growth of all plants: C, H, O, N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Mo, B, and Cl in various ionic forms. Interestingly, soil microbes require these same elements. In undisturbed ecosystems, plants obtain these nutrients from the soil solution via mineral weathering, atmospheric inputs, inputs from stream deposition, and nutrient recycling due to death and decomposition of vegetation. The availability of the nutrients depends on abiotic soil factors (Chapter 2) and chemical and biological properties (Chapters 5 and 7). Agricultural crop production has always relied on soil components for nutrient sources. However, excessive cropping and in particular dense monoculture practices deplete soil plant nutrients, especially N, P, K, and Ca. Thus, over years of continuous crop production, large amounts of nutrients are removed, with a concomitant decline in productivity. Therefore, N, P, K, and other plant nutrients must be periodically augmented by the use of fertilizers, including animal or human wastes. Fertilizers may contain any of the essential nutrients, but the majority of fertilizers applied to agricultural soils contain nitrogen (N), phosphorus (P), potassium (K), or some combination thereof. These are the so-called **macronutrients** because plants take them up in larger amounts than the other essential nutrients.

Figure 16.8 illustrates trends for macronutrient use in the United States. Fertilizer use dramatically increased around the time of World War II, as improved crop varieties and management practices, together with increased mechanization,

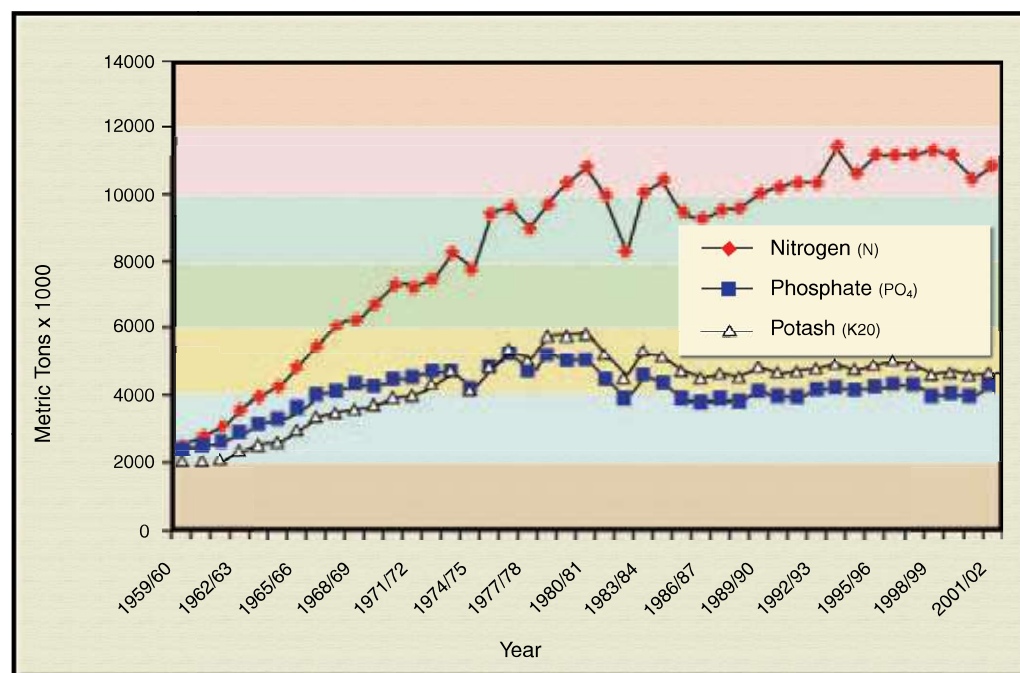


Figure 16.8 Historical trends for fertilizer nutrient use in the United States. Data source: The Fertilizer Institute (TFI, 2005).

made fertilizer use both practicable and profitable. In the 1980s, however, fertilizer use began to level off, reflecting both lower agricultural profitability and increased environmental concerns related to fertilizer use. Nonetheless, the combined annual per capita use in the U.S. of NPK fertilizers is about more than 150 lbs (~70 kg). The aforementioned concerns associated with the use of NPK fertilizers and wastes include excessive surface and groundwater pollution by water-soluble nitrates and colloid-bound phosphates due to poor agricultural fertilizer and waste management practices (see also Chapters 17 and 18).

16.6.2 Pesticides

Extensive use of synthetic pesticides began in the 1940s with DDT used to control mosquitoes. This was quickly followed by the adoption of pesticides in large-scale monocultural agricultural production. Initially pesticide use was credited with significant increases in food production. However, the negative aspects of their indiscriminate use also became evident. For example, extensive use of insecticides and herbicides has created new generations of pesticide resistant insects and plants.

In 1962, Rachel Carson's book *Silent Spring* brought public attention to the fact that chlorinated pesticides were very persistent in the environment. These chemicals can accumulate in animal fatty tissue and produce fish kills when released into waterways. DDT, associated with the rapid decline of some birds of prey, was banned for agricultural use in the United States in 1973. Other chlorinated pesticides were also banned, but have been replaced by much less persistent, but more acutely toxic, pesticides. In addition, in recent years new links have been discovered between some

types of cancer and low-level exposure to some pesticides like 2,4-dichlorophenoxyacetic acid (2,4-D), 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), and other pesticides.

Less persistent pesticides are usually much more soluble in water than chlorinated hydrocarbons. Unfortunately, these new pesticides are more like to leach to groundwater or be found in the agricultural runoff if they are not degraded fast enough in the soil environment (see section 16.6.2.3). Today, pesticides continue to be used extensively in modern farming, urban lawns, parks, and golf courses primarily to control weeds, fungi, and insect infestations. Unfortunately, even less persistent pesticides have their problems. In 2003, the U.S. EPA concluded that atrazine, the second most widely used pesticide (herbicide) in the U.S., could cause sexual abnormalities in frogs. In addition, atrazines, the most common family of herbicide chemicals found in groundwater are also potential endocrine disruptors. Other common pesticides have been linked to or are being studied as possible endocrine disruptors (see Chapter 31).

16.6.2.1 Types of pesticides

The technical definition, stated in the amended **Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)**, is that a pesticide is any substance or mixture of substances intended for destroying, preventing, or mitigating insects, rodents, nematodes, fungi, weeds, or any other undesirable pests. This also includes plant or insect growth regulators as well as defoliants that are used to cause leaves to drop from plants to facilitate harvest, and desiccants that dry up unwanted plant tissue. Under this definition, many chemicals, both newly developed and familiar, may be considered as pesticides and be regulated as such. For example, insect pheromones (sex

attractants) may be used to attract certain insect populations, to confuse mating patterns, and thereby control insect population. In addition, ordinary dish detergent may be used to kill whiteflies or bees. Common table salt (sodium chloride) is used to control weeds in beet fields in humid regions.

Insecticides are formulated to control particular insects. Two common insecticides are chlorpyrifos and malathion. Herbicides are formulated to control weeds. Glyphosate and atrazine are the two most common herbicides, accounting for 70–90% of the total herbicide use in the U.S. (US EPA, 2004). Fungicides are formulated to control fungi including molds and mushrooms. Chloropicrin, metam-sodium and 1,3-dichloropropene are the three commonly used fumigants applied to soil to control nematodes and soil fungi in the U.S. (USEPA, 2004).

Pesticides may also be classified according to their mode of entry into the target pest. Contact pesticides enter the target pest upon direct application, while systemic pesticides must pass through a host organism before they enter their targets. For example, a contact insecticide, or its residue, kills target plants or insects on direct application, while a systemic insecticide kills insects only after moving through the system of the plant hosting the target insect. Thus, if a particular insect does not feed on the plant, it will not be harmed.

Finally, pesticides can be classified by the forms in which they are used. Fumigants, for example, are pesticides applied as gases. Fumigants may be used selectively to control drywood termites in houses or to control the pest population in stored products such as fruits, vegetables, and grains. They may also be released over large areas to remove many pests from soil.

16.6.2.2 Extent of pesticide use

Pesticides are sold or distributed by intra- or interstate commerce in the United States, and they must be registered by the U.S. EPA. The EPA has compiled substantial lists of

pesticide ingredients whose applications must be reported. The EPA is also authorized, by the **Federal Food, Drug, and Cosmetic Act (FFDCS)**, to establish tolerances for pesticide residues in raw and processed foods. The **Food and Drug Administration (FDA)** of the Department of Health and Human Services monitors and enforces the established tolerances (see also Chapter 15).

In addition, many individual states in the United States have established other regulatory agencies to control pesticide applications in order to protect wildlife and water supplies. For example, Arizona has compiled a list of chemicals—the Groundwater Protection List—whose use must be reported. Similar requirements exist for the sales of these pesticides, so that significant underreporting of applications cannot occur without alerting the regulatory agency.

According to the U.S. EPA, in 2001 the use of conventional pesticides in the U.S. was estimated to be about 1.2 billion lbs (545 million kg), reflecting a slightly declining trend in use since the mid-1980s (Figure 16.9). These figures place the annual per capita use of pesticides at about 4 lbs (~1.9 kg). The U.S. EPA estimates that in 2001 about 78% of these products were used in agricultural production; 12% in home and garden settings; and the remaining 10% in forestry, industry, and government programs. Therefore, most of these chemicals were applied directly onto plants and animals on agricultural lands and water systems. In addition, industry and water utilities also use chemicals with pesticide-like properties. For example, according to U.S. EPA estimates in 2001, about 790 million lbs (360 million kg) of wood preservative chemicals and 2.6 billion lbs (1.19 billion kg) of chlorine and hypochlorite chemicals were used in the U.S. These highly toxic chemicals include creosote, pentachlorophenol, and CCA (chromate copper arsenate). Presently, pesticide product labeling must list their active ingredients and the EPA's registration number, as well as safe use instructions to minimize personal exposure and damage to soil and water environments.

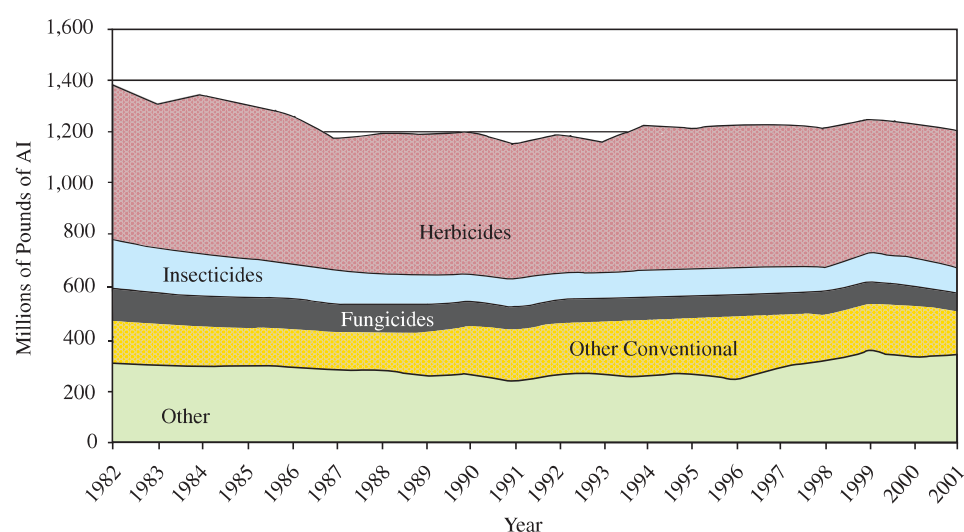


Figure 16.9 Annual amount of pesticide active ingredient used in the U.S. by pesticide type, 1982–2001 estimates. All market sectors. From U.S. EPA, 2004.

It is interesting to note that despite the public awareness about numerous links between pesticide residues, their adverse health and environmental effects, and the increasing public demands for pesticide-free food, the largest growth sector for pesticides is in home and garden applications. Since 1995, the use of pesticides by the private sector (home and garden) has nearly doubled (from 7% to 12% in 2001) (U.S. EPA, 2004).

16.6.2.3 Fate of pesticides

Depending upon their physicochemical properties, patterns of use, and local conditions, some pesticides may leach through the crop root zone and eventually contaminate groundwater at certain locations (see Chapter 17). The two most important properties of a chemical that determine whether a pesticide represents a threat to groundwater are its *persistence* and *mobility* in soil, as discussed in Chapter 6. During the registration of new pesticides, computer programs are used to estimate the potential for groundwater to be contaminated by the specific use of a particular chemical at various locations in the United States. Several states, including Arizona and California, consider the capacity of a compound to leach through the soil into groundwater as a criterion for inclusion in their lists of controlled chemicals.

After a pesticide is applied to a field, it may meet a variety of fates, as shown in Figure 16.10. Some may be lost to the atmosphere through volatilization, carried away to surface waters by runoff and erosion, or photodegraded by sunlight. Pesticides that have entered into soil may be taken up

by plants (and subsequently removed), degraded into other chemical forms, or leached downward with water below the crop root zone. The amount of any particular chemical that ends up volatilized, leached, degraded, or in surface runoff depends upon site conditions, weather conditions, management practices, soil properties, and pesticide properties (as described in several previous chapters).

In evaluating the contamination potential of a particular pesticide, it is essential to consider its sorption (retardation) and transformation half-life behavior jointly, as discussed in Chapter 6. For example, a pesticide with low retardation and a long half-life (*e.g.*, more than 100 days) poses a considerable threat to groundwater through leaching, particularly in soils having low organic matter. Conversely, a pesticide with large retardation and a long half-life is more likely to remain on or near the surface of soils with moderate levels of organic carbon content, thereby increasing its chances of being carried to a lake or stream in runoff water. In terms of water-quality protection, pesticides with intermediate retardation and short half-lives may be considered the “safest.” Although they are not readily leached, they move into the soil with water, thereby reducing their potential for loss from erosion, and they degrade fairly rapidly, thereby reducing the chance for losses below the root zone. Figure 16.11 provides a schematic representation of the depth of movement of a strongly sorbed (glyphosate), a moderately sorbed (atrazine), and a weakly sorbed (aldicarb) chemical. It was assumed that the rainfall and irrigation amounts exceeded the crop water use by twice the amount of water contained in the root zone at an optimum water content that moved the chemicals downward.

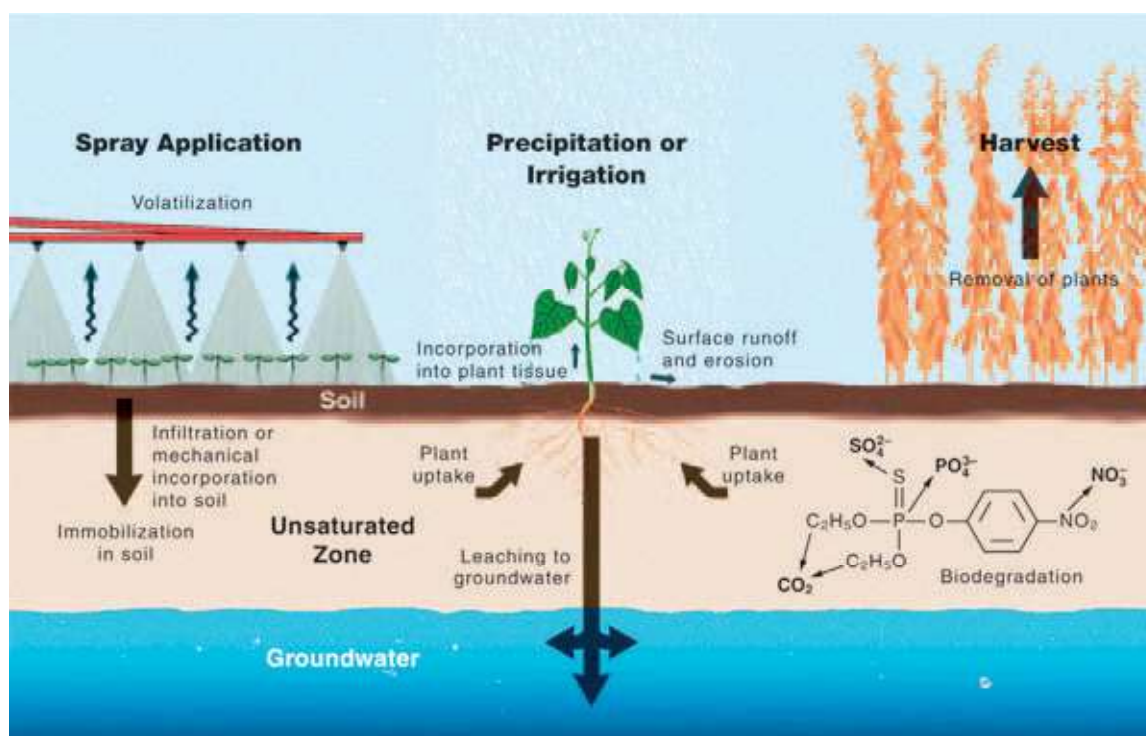


Figure 16.10 Fate of pesticides in soil. From *Pollution Science* © 1996, Academic Press, San Diego, CA.

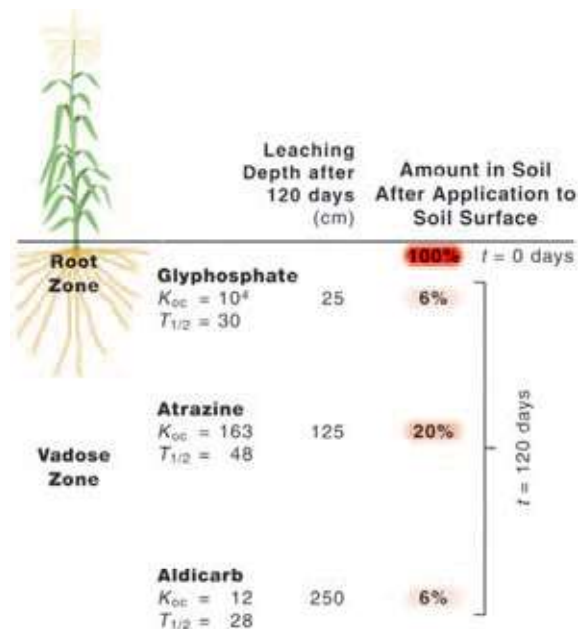


Figure 16.11 Relative movement and persistence of pesticides in soil. The transport of a particular pesticide is strongly influenced by retardation. Here, the degree of retardation increases in the order aldicarb < atrazine < glyphosate. The amount of pesticide remaining in the soil is illustrated by the intensity of color 120 days after the application. From *Pollution Science* © 1996, Academic Press, San Diego, CA.

As shown in Figure 16.11, glyphosate would be concentrated in the root zone to a depth of about 25 cm, atrazine would be concentrated near the bottom of the root zone (about 125 cm), and aldicarb would be concentrated at a depth of about 250 cm. A slightly higher percentage of the applied atrazine would exist in the system, compared with the other two pesticides, because it has a slightly larger half-life. For a growing season of about 120 days, about 6% of the applied aldicarb and glyphosate would remain, while about 20% of the atrazine would remain. This example does not account for numerous differences in management practices that would influence the persistence and soil distribution of these pesticides.

16.7 ANIMAL WASTES

Animal wastes contain several types of land pollutants that are of increasing concern both to the public and regulators. Besides traditional pollutants, discussed below, increasing evidence suggests that excessive use of animals waste on land releases measurable amounts of antibiotics, growth hormones, and pesticides containing toxic metals like arsenic. Animal agricultural wastes can be divided by two production types: range and pasture production, and confined or concentrated animal production.

In range and pasture systems, the concentration of wastes is generally much more diffuse or dispersed than it is when large numbers of animals are confined to relatively small areas. Range and pasture systems have two principal measurable effects on surface water quality: (1) increased turbidity through the movement of soil particles into streams, rivers, and lakes; and (2) increased fecal coliform counts in areas of heavy animal use. Although we know that grazing systems may adversely affect some measures of water quality, we will focus here on the highly concentrated animal production units and the methods of preventing and controlling pollution from these concentrated units. Concentrated animal production is very common and is occurring in increasingly controlled environments to raise productivity and diminish climatic, feeding, and mortality variables. Larger numbers of animals are being raised in **concentrated animal feeding operations** or **CAFOs**—principally, feedlots, dairies, swine operations, poultry houses, and intensive aquaculture.

Following World War II, manure was displaced as the primary fertilizer by fossil-fuel-based fertilizers as farms became increasingly specialized.

With the breakdown of the traditional cycle of reincorporation of wastes back in to the land, what was once an essential source of nutrients has now become a potential pollutant. Thus, the production of large numbers of animals on a small land base has resulted in the stockpiling of wastes, the construction of large waste-storage ponds, and, oftentimes, waste applications to land in excess of agronomic crop needs. To date, few states regulate the land application of animal wastes to the degree that biosolids are regulated (see Chapter 27).

16.7.1 Nonpoint Versus Point Source Pollution

The term “nonpoint pollution” is misleading and is often misused in the context of animal wastes. In animal agricultural systems, true **nonpoint sources** are those in which potential contaminants are not concentrated during production and do not pass through a single or small number of conduits for disposal. These nonpoint sources include corrals, feedlots, and extensive and intensive pasture systems.

Point sources are those facilities that concentrate pollutants or contaminants to a significant degree and pass these contaminants through a pipe, ditch, or canal for disposal. The most common point sources are milksheds and barns, dairy and other food-processing plants, intensive indoor swine facilities, anaerobic and aerobic lagoons, and evaporative storage ponds. In addition, certain types of intensive aquaculture may also be point sources of contaminants, with return flows highly nutrient-laden with fish excreta.

According to EPA regulations, however, some concentrated animal feeding operations may be designated as point sources requiring an individual National Pollution Discharge Elimination System (NPDES) permit. In this case, a concentrated animal feeding operation is defined as a lot or facility

without vegetation where animals are confined for 45 or more days per year. The number of animals needed to meet this definition as a CAFO depends on several factors;the key determinant is whether or not the facility discharges into navigable waters, as determined by the method of discharge. The method of discharge is judged by the 25-year, 24-hour storm event, which is the required event that a facility must be designed to meet.

Nonpoint sources, such as nondischarging concentrated animal feeding operations, require a different approach to prevention and mitigation of pollutants than do point source emissions from a pipe or conduit. At present, the nonpoint source approach to mitigation employs **Best Management Practices (BMPs)**, as defined by the 1987 Amendments to the Federal Water Pollution Control Act. In contrast, point source methods employ methods termed **Best Available Demonstrated Control Technology** or **Best Available Control Technology**. In 2003, the U.S. EPA (2003) published a Final Rule on CAFOs that is now used to permit animal feeding operations by establishing requirements that are more protective of the environment. Large amounts of animal wastes are land applied (see Chapter 27).

16.7.2
Specific Pollutants

Concentrated animal agriculture produces specific pollutants in the wastes resulting from animal metabolic activity (Information Box 16.1).

INFORMATION BOX 16.1

Specific Pollutants in Animal Wastes and Common Environmental Effects

Nitrate-nitrogen:	Excessive plant/microbial growth
Phosphates:	Surface water eutrophication
Salts:	Soil salinity
Pathogens such as fecal coliform bacteria, <i>Salmonella</i> , <i>Giardia</i> , <i>Campylobacter</i> , and <i>Cryptosporidium parvum</i> :	Water contamination
Pesticides, antibiotics, and growth hormones:	Endocrine disruptors
Carbon dioxide (CO ₂):	Global warming
Hydrogen sulfide (H ₂ S):	Odor
Ammonia (NH ₃):	Odor
Methane (CH ₄):	Global warming
Arsenic:	Water contamination

16.8
INDUSTRIAL WASTES WITH HIGH SALTS AND ORGANICS

16.8.1
Oil Drilling

The process of drilling for crude oil requires powerful drill rigs that use large quantities of drilling fluids. These fluids contain high-density weighing agents such as barium sulfate (barite). Other drilling fluids are composed of sodium chloride solutions, which are used to force crude oil up to the surface. These fluids must be disposed of once they are “spent,” or no longer useful. Prior to 1985, these spend fluids were stored in ponds near the drill sites and often simply bulldozed over when the well was completed. Consequently, many older oilfields have large tracts of land contaminated with spent drilling wastes. These wastes are not considered hazardous because they do not contain significant amounts of metals. Although free barium is very toxic, the mineral barite (BaSO₄) is quite inert in the environment. On the other hand, NaCl is very soluble in water and can increase the salinity of surface waters, rendering them nonpotable.

16.8.2
Coal-Burning Electric Power Plants

Electric power plants produce millions of tons of **fly ash** and **flue gas desulfurization wastes** every year. Because these residues are not considered hazardous, they may be stored either in ponds or landfills or, in the case of fly ash, they may be used as fill material. Fly ash is recovered from electrostatic precipitators that scrub out silt-size particulate matter from the flue gases generated from coal combustion. These particles generally arise from the incombustible silt and clay found in coal deposits. Upon exposure to high temperatures, silt and clay (which consists mostly of silica and alumina) combine to yield amorphous Si–Al-based spheres onto which other elements may condense. Typically, fly ash spheres also include Ca, Na, Fe, Mg, K, and Ti, with small amounts of other elements sorbed onto them, such as As, B, Ba, Cd, Cr, Cu, F, MO, NI, Pb, S, and Zn. The concentrations of these elements in fly ash vary widely, depending on the source of the coal. A typical empirical composition of fly ash is

$$10 \text{ Si} + 5 \text{ Al} + 0.5 \text{ Ca} + 0.5 \text{ Na} + 0.4 \text{ Fe} + 0.2 \text{ Mg} + 0.2 \text{ Mg} + 0.2 \text{ K} + 0.1 \text{ Ti} + 0.05 \text{ S} + \text{trace amounts of more than 15 other elements}$$

The removal (scrubbing) of sulfur dioxide (SO₂) gas from flue gases produces large quantities of flue gas desulfurization wastes, which consist largely of calcium carbonates, sulfates, and sulfites. These wastes may also contain trace quantities of some of the elements in fly ash, but the concentration of these elements depends on the source of the coal and the type of scrubbing systems used. Because flue gas desulfurization products are usually more than 70% water, these wastes are disposed of in drying ponds and are often treated along with power-plant wastewaters. This waste mixing may add significant amounts of soluble

salts (*e.g.*, NaCl) that increase the salinity of sludges (see Table 24.2).

Despite new gas scrubbing technology and stricter emission standards, sulfur dioxide and nitrous oxide have been reduced but not completely eliminated. For example, current emissions of these two acid-forming gases still exceed 10 million tons/year. However, significant reductions (>60%) are mandated by the U.S. EPA in the next 16 years via a new **Clean Air Interstate Rule (CAIR)**, which affects 28 eastern U.S. states.

Mercury metal emissions from coal-burning electric power plants have also been a controversial issue. For the first time, reductions in Hg emissions from coal-burning power plants are being mandated under the new March 2005 **Clean Air Mercury Rule**. Under this rule, by 2020, reductions of 70% Hg emissions are expected from coal-burning power plants.

16.8.3 Industrial Wastes High in Organic Chemicals

Most industrial wastes contain varying amounts of organic chemicals. With few exceptions, carbon-based chemicals, reagents, solvents, feedstocks, and raw materials are extensively used in most phases of industrial processing. Exceptions to this rule may include mine tailings and metal-plating wastes. Wastes high in organic chemicals include those originating from oil refineries, as well as petrochemical, chemical, pharmaceutical, and food-processing industries, and paper mills. However, in recent years, these industries have reduced their polluting waste streams by applying aggressive pollution prevention strategies such as wastewater treatment processes before discharge, the implementation of waste reduction techniques that include recycling, and changes in industrial process with emphasis on waste minimization processes (see also Chapter 21).

16.9 INVASIVE SPECIES

Invasive species are an environmental problem of growing concern worldwide. Invasive species are organisms that have been introduced to a new ecosystem and that have a severe, often irreversible effect on agriculture and natural ecosystems (see Information Box 16.2). Any organism can become an invasive species, including microorganisms, invertebrates, insects, fish, plants, and animals. Invasive organisms often find few enemies (predators and diseases) in their new location, allowing them, at least initially, to grow and reproduce relatively easily.

It is important to note that a key component of this issue is that humans typically introduce the invasive species. Species can gradually spread into new areas as a natural process; this process is usually slow and involves adjustments by all members of the ecosystem. Conversely, human introductions are usually relatively fast, often resulting in large

INFORMATION BOX 16.2

Invasive Species and Associated Problems

Invasive species:	Non-native species, introduced to a new area primarily by human activity, that can reproduce and spread independently and that cause, or is likely to cause, economic or environmental damage.
Invasive species problems:	Competition with and replacement of native species, damage to wildlife habitat, altered fire ecology, potential to spread disease.

disruptions of the ecosystem. As noted in Information Box 16.2, these disturbances can be obvious or subtle.

In most cases, invasive species take advantage of opportunities in ecosystems that are disturbed by human activity (see Information Box 16.3). Disturbances can be flow control of rivers, disturbed soil along roadways and agricultural areas, human structures (*e.g.*, pigeons and sparrows are better adapted to cities than many native birds), water temperature change due to power plant outflows, and so on.

Some invasive species were introduced to provide erosion control, such as kudzu and salt cedar. Others, such as Lehman lovegrass and red brome, were repeatedly introduced over large areas of the western U.S. as forage grasses for cattle and sheep. These grasses have radically altered the fire ecology of western ranges, which in turn has changed plant populations, wildlife distribution, and nutrient cycling. Other invasive species escaped from gardens. A widely known example is purple loosestrife, which is a colorful perennial plant that is prized in gardens. Purple loosestrife has spread widely in the eastern and northern U.S., choking waterways and supplanting native riparian species. Animals released as hunting stock have caused problems. Examples include opossums in the northwestern U.S., rabbits in Australia, and red deer in New Zealand. Invasive Zebra mussels in the Great Lakes have caused millions of dollars worth

INFORMATION BOX 16.3

Adaptive Traits of Invasive Species

- High reproductive rates
- High dispersal rates
- High genetic variability (allows them to adapt more quickly to a broad range of environmental conditions)
- Broad range of native habitat, *i.e.*, adapted to a variety of soil and climatic conditions
- Moved by humans to new locations, whether deliberately (kudzu) or accidentally (tumbleweed)



Figure 16.12 Kudzu is an invasive perennial vine that grows over everything in its path, including trees and buildings. (A) A cabin in early spring, with kudzu visibly starting to climb on trees and the abandoned cabin. (B) The same location in late summer, showing kudzu that has covered the cabin and most of the bushes and trees in the foreground. Kudzu blocks light from reaching the plants underneath, greatly weakening them, and can become heavy enough to break branches. Photo courtesy Jack Anthony (www.jjanthony.com/kudzu).

of damage to water intake systems, while simultaneously decreasing lake biodiversity. Fire ants (*Solenopsis invicta*) decrease biodiversity while causing major economic damage.

16.9.1 Kudzu

Kudzu (*Pueraria montana* var. *lobata*) is a well-known, highly visible example of an invasive plant species. Kudzu is a broad leaved, fast growing perennial vine (Figure 16.12) from Japan that was deliberately introduced in the early 1900s to control erosion and provide forage in the southern U.S. Kudzu grows rapidly and stabilizes loose soil with large, fleshy roots. In the U.S., kudzu has few serious checks on its growth by insects or disease, which allows it to grow as much as 20 m (60 feet) per season. This growth tends to completely cover existing vegetation, and can break branches and block sunlight from the native plants, eventually greatly weakening or killing them. Kudzu can also cover cars and entire buildings. Once it is well established, kudzu is difficult to remove. In addition, there is some evidence that kudzu is becoming more cold tolerant, extending its range to the north. It is estimated that kudzu covers about 25,000 square kilometers (10,000 square miles) in the U.S. and that it costs somewhere between \$100 million to \$500 million dollars a year in lost cropland and control costs.

16.9.2 Salt Cedar

Kudzu is quite obvious, even to the untrained eye, and causes visible damage as it smothers other plants and buildings with its extremely rapid growth. Many invasive species do not cause such obvious problems. Salt cedar (*Tamarix* spp.) has rapidly colonized riparian areas throughout the western U.S., causing major changes in this habitat. These changes are not obvious to the casual observer and yet are causing profound changes in riparian ecosystems.

Multiple species of salt cedar were originally introduced more than 100 years ago for erosion control and ornamental use (Figure 16.13). Salt cedar is tolerant of drought and saline and alkaline soils, grows quickly if there is sufficient water, has high seed production, and resprouts easily after fire. In addition, salt cedar has been implicated in lowering water tables at the expense of native species and also of salinizing soil. It is generally thought that these characteristics have enabled them to supplant native stands of cottonwood (*Populus* spp.) and willow (*Salix* spp.) that provide wildlife habitat, while producing little useful habitat of their own. As a result, land managers consider salt cedar a prime example of a detrimental invasive species.

Salt cedar is now found throughout the western U.S., thriving in response to human disturbances related to dams and diversion projects along large drainages. Research indicates that salt cedar changes the species composition of riparian communities and reduces their biodiversity (see Chapter 20). Thickets of salt cedar tend to replace native shrubs and trees such as willow and cottonwood, generally without replacing their usefulness as nesting sites and food sources. This may be due in part to the control of floods by dams, as willows and cottonwoods tend to establish new seedlings after flood events. In addition, regulation of river flow in general is causing many riparian areas to become drier and more saline. Recent research indicates that salt cedar may be better adapted to these new growing conditions, which allows them to outcompete the native species.

Salt cedar is also widely regarded as a cause of salinization of soil, which is thought to prevent or diminish the growth of many native species. Salt cedar is very tolerant of salinity and is able to use low-quality surface and ground-water sources that many natives cannot. The plants store excess salts in salt glands in the leaves and also excrete salt onto the surface of the leaves themselves. Since



Figure 16.13 Salt cedar thickets growing along the edge of a seasonally dry retention pond with high salinity in the southwestern U.S. Dark shrubs on the hills above the salt cedar are juniper. The insert shows a flowering salt cedar. Photo courtesy J.F. Artiola.

salt cedar is deciduous, the leaves eventually fall to the soil surface and build up a salt-rich litter. In areas with floods or sufficient rain, this salt is moved out of the root zone, but salt cedar usually grows in arid areas with low rainfall and along regulated waterways (preventing regular floods), thus allowing some salt buildup. Recent research indicates that there may not be salt buildup over a period of years, as rains and occasional floods may leach the salt out of the root zone. Other research indicates that the salt buildup is small enough that it does not affect some of the more salt-tolerant native species.

There is no doubt that salt cedar is an invasive species. Land managers are finding it difficult to remove salt cedar and re-establish native populations, and have blamed salt cedar for drier conditions and more saline soil. However, salt cedar may instead be able to adapt more readily than some native species to human-caused ecosystem disturbances.

Invasive species have caused major ecosystem changes throughout the world, resulting in billions of dollars of damage to agriculture, forestry, power plants, and the like each year. They are almost impossible to eradicate and difficult to control once established (see Chapter 20).

QUESTIONS AND PROBLEMS

1. Explain why mine tailings can be a source of pollutants in the soil and air environments. Give two examples of pollutants associated with mine tailings.
2. Give two examples of land pollution associated with deforestation.
3. Soils can become acidic when (a) basic cations are leached, (b) Al-oxides accumulate, (c) carbonate and bicarbonate minerals disappear, or (d) all of the above. Explain your answer.
4. What is the difference between a saline and a sodic soil? Explain the difference, and the EC and ESP values that a soil would have to have to be called saline-sodic.
5. Which factor would you add to or replace in the water erosion model RUSLE equation presented in Section 16.5.1 to make it a wind erosion model?
6. Explain why aggregated fine particles are less affected by wind erosion than loose coarser soil particulates.
7. Give two examples (each) of chlorinated and nonchlorinated pesticides and their use.
8. Why are chlorinated pesticides more persistent in the environment than nonchlorinated pesticides?
9. Explain how invasive plant species can change soil salinity and water quality.
10. Explain how deforestation affects water quality.

REFERENCES AND ADDITIONAL READING

- Anthony J. (2005) Kudzu, The vine. www.jjanthony.com/kudzu.
- Blake J., Donald J. and Magette W., eds. (1992) National livestock, poultry and aquaculture waste management. Proceedings of the National Workshop, July 1991. American Society of Agricultural Engineers, St. Joseph, Michigan.
- Bonan G. (2002) *Ecological Climatology*. Cambridge University Press, Cambridge, England.
- TFL. 2005. U.S. fertilizer use statistics. <http://www.tfi.org/Statistics/Usfertuse2.asp>.
- Borman F.H. and Likens G.E. (1979). *Pattern and Process in a Forested ecosystem*. Springer-Verlag, New York.
- Bucklin R., ed. (1994) Dairy systems for the 21st century. Proceedings of the 3rd International Dairy Housing Conference, 1994. American Society of Agricultural Engineers, St. Joseph, Michigan.
- Glenn E.P. and Nagler P.L. (2005) Comparative ecophysiology of *Tamarix ramosissima* and native trees in western U.S. riparian zones. *J. Arid Environ* **61**, 419–446.
- Guptka R.K. and Abrol I.P. (1990) Salt-affected soils: Their reclamation and management for crop production. In R. Lal and B.A. Stewart (1990) *Soil Degradation: Advances in Soil Sci.* **11**, 223–288. Springer-Verlag, New York.
- Heald C.L., Jacob D.J., Fiore A.M., Emmons L.K., Gille J.C., et al. (2003) Asian outflow and trans-pacific transport of carbon monoxide and ozone pollution: An integrated satellite, aircraft, and model perspective. *J. Geophys. Res.* **108**(D24), 4804, doi:10.1029/2003JD003507.
- Hegg R.O. (2005) Trends in animal manure management research. CRIS database. Symposium State of the Science Animal Manure and Waste Management, January 5–7, 2005. San Antonio, Texas.
- Luken J.O. and Thieret J.W. (1997) *Assessment and Management of Plant Invasions*. Springer-Verlag, New York.
- Merkel J.A. (1981) *Managing Livestock Wastes*. Avi Publishing Company, Westport, Connecticut.
- Saxton K., Chandler D., Stetler L., Lamb B., Clairborn C. and Lee B.H. (2000) Wind erosion and fugitive dust fluxes on agricultural lands in the Pacific Northwest. *Trans. ASAE* **43**, 623–630.
- Stumm W. and Morgan J.J. (1996) *Aquatic Chemistry*, 3rd Edition. A Wiley-Interscience Series of Texts and Monographs. John Wiley & Sons, New York.
- Texas Environmental Profiles. <http://www.texasep.org>
- USDA. (1954) Saline and sodic soils. Agriculture Handbook No. 60. United States Department of Agriculture.
- USDA-CREES. <http://www.usawaterquality.org>
- U.S. EPA. (2004) Pesticide Industry Sales and Usage—2000–2001 Market Estimates. Biological and economic analysis division—Office of Pesticide Programs. Office of Prevention, Pesticides, and Toxic Substances. U.S. Environmental Protection Agency. Washington, DC 20460. May 2004.
- U.S. EPA-CAFO Final Rule (2003) <http://www.usawaterquality.org/themes/animal/default.html>.
- Veiga M.M., Meech J.A. and Oñate N. (1994) Mercury pollution from deforestation. *Nature*. **368**, 816–817.
- Zhang H., Henderson-Sellers A. and McGuffie K. (2003) The compounds effects of tropical deforestation and greenhouse warming on climate. *Climatic Change*. **49**(3), 309–338. 10.1023/A:1010662425950.