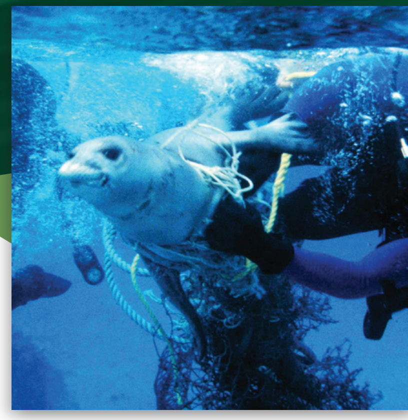


CHAPTER 22

Environmental Impacts of Industrial Activities and Human Populations

It is hard to believe that many of today's most polluted coastal waters once brimmed over with fish and shellfish. In the early nineteenth century, the waters of metropolitan New York City were a culinary delight. Raritan Bay, now close to the largest landfill in the world, once harbored some of the richest oyster beds in America, and the East River was a paradise for sports fishing. Commercial shell fishing and finfishing were major enterprises. Needless to say, times have changed. The arrival of the Industrial Revolution and the sudden flowering of New York City brought along major habitat deterioration. In New York, the oyster beds are gone, and any remaining shellfish are often dangerous to eat. Fishes are often tainted with toxic substances, and those depending on the bottom are reduced in abundance and diversity. This pattern of decline is typical of urbanized coasts throughout the world. On the other hand, efforts in recent decades have been partially successful in reducing inputs of pollutants. In the Hudson River, mercury in common fishes has declined about two thirds. Still, human impacts are widespread. About 41 percent of the ocean is affected by multiple stressors (Halpern et al., 2008). If toxic substances have been reduced in some areas, they are still on the rise in others. Global climate change adds another layer of stress to the entire oceanic system.

Human Effects on the Marine Environment

■ **Complex interactions of human impacts often make it difficult to understand the role of various pollutants in degrading the marine environment.**

Polluted areas usually are affected by several types of human impacts, which can combine in complex ways to cause biotic degradation, making difficult both the quantification of the degradation and the management decisions on which problem to address. Sediments in most urban harbors are a complex mix of natural sands, silts, and clays, as well as a large number of substances from industrial sources, sewage, and atmospheric deposition. The joint toxic effects of these inputs create difficulties in determining the specific sources of toxicity and effects on organisms.

Human effects on the marine environment may be divided into the following general categories:

1. *Direct habitat destruction.* Alteration of bottom substrate and hydrodynamic conditions through dredging, changing of shoreline structures, and filling.
2. *Toxic substances.* Introduction of chemical substances dangerous either to marine life or to humans.
3. *Sewage, wastewater, and agricultural sources rich in nutrients.* Release of sewage and more generalized sources rich in nutrients used by marine microorganisms.
4. *Heating and water interception.* Effects of power plants, which heat effluent water and capture on screens larval and juvenile marine organisms.
5. *Climate change.* Effects of greenhouse gas emissions on climate and ocean acidification (discussed earlier in this volume).

■ **Pollution may be long term (chronic) or short term (acute).**

It is convenient to divide the effects of pollution into **long-term (chronic) effects** and **short-term (acute) effects**. Chronic pollution involves the introduction of a toxic substance or other anthropogenic factor continuously, causing a degradation of the environment. Year-round inputs of nutrients derived from sewage is a good example. An oil spill is an example of a short-term acute effect. At first, oil often has catastrophic effects on a marine biota, but these effects may gradually be ameliorated as the oil breaks down.

■ **Pollution may come from point sources or from a variety of geographic points.**

Pollution often comes from a **point source**, such as a single sewer pipe or factory wastewater outfall. In such cases, the concentration of the substance or the intensity of the effect (e.g., temperature near a power plant outfall) should decline with increasing distance from the point source. The nature of the decline depends on the rate of introduction, physicochemical properties of the substance or factor, the water currents, and the sedimentary environment. Such cases are relatively simple in terms of identification and management because a regulatory agency can find the source and monitor the spatial extent of its effects. Mobile organisms may also transport toxic substances by picking them up near a point source and swimming far away. By contrast, **nonpoint source** effects cannot be attributed to any single spot. Runoff following rain is a good example of a nonpoint source: Toxic substances and fertilizer-derived nutrients may then be swept into a basin over a broad extent of the coast, or seep through groundwater into a coastal basin. Such sources are far more difficult to manage because the source cannot be cleaned up as directly as material emanating from a pipe.

Measuring the Impact of Pollutants on Populations and Communities

While it may often be a challenge to identify and measure the concentration of a pollutant, an even greater challenge is to assess the impact of the substance on natural populations and communities. When appropriate baseline data are available, a number of criteria may be used to gauge human impact on a marine environment. These involve effects on single species, effects on communities, such as transfer of toxic substances through food webs, and more general effects on overall community parameters such as biodiversity and trophic structure.

Measuring Effects on Single Species

■ **Common species are often chosen as bioassays of pollution effects.**

In some cases, certain common or vulnerable species are used as measures of the effects of pollution. The absence of the species, increased mortality, reduced reproduction, or impaired physiological performance may be used as evidence of environmental degradation. For this purpose, much applied biological research has been concentrated on a few common marine species or species used as representative models of pollution impacts. For example, species of the marine mussel genus *Mytilus* have been investigated extensively, and the effects upon it of varying food, temperature, and toxic substances have been measured. In the United States, species of the amphipod *Ampelisca* are used commonly to assay the toxicity of sediments. A method known as *Microtox* employs the effects of a presumed toxic substance or sediment on the light output of a luminescent bacterium growing among the sedimentary grains. Oyster larvae are also used as bioassay organisms because we believe that early developmental stages are more sensitive to pollution than adult stages and mortality of larvae has a great impact on the fate of a marine population.

The use of model species has led to the concept of **bioassay**, which is the measurement of some parameter in a "model" species after being exposed to a stress. The **bioassay species** is usually selected for its natural abundance and ease of rearing. A population is exposed to a range of concentrations of a toxic substance. Mortality rate, uptake rate of the toxic substance, or impairment of physiological function can then be measured. The **LC_{50}** is the concentration of a toxic substance that produces 50 percent mortality in an experimental population after a specified time. The reciprocal of the LC_{50} can be used as a measure of tolerance. Estimates of **sublethal responses** are preferred because widespread effects of toxic substances might be operating at concentrations much below the concentration needed to cause mortality. It is useful to measure the relationship between concentration of the toxic substance and oxygen consumption, which is a measure of metabolic rate. One integrating measure of physiological condition is **scope for growth** (see Chapter 5). Increasing exposure to a toxic substance might encumber a metabolic cost at the whole-animal level and reduce scope for growth. On a smaller scale, cellular assays could be usefully employed. One approach is to estimate **cellular energy allocation**, by quantifying cellular energy reserves and measuring mitochondrial activity. On a DNA level, responses of gene expression can be studied through transcriptomic and proteomic assays.

Before laboratory tests are conducted, indicators of pollution effects may be assayed in individuals collected from field populations, such as abnormal body weight or development of abnormal structures. For example, in many gastropods one can find females with extensive development of male anatomical parts including a penis and a vas deferens. Such individuals occur in greater frequency in the presence of toxic metals, and the percentage of females with such male development turns out to be a good indicator of the toxic effects of tributyltin (TBT), a component of antifouling paint once used extensively on boats and still used in U.S. naval vessels. The development of a vas deferens in affected females can block the genital pore and curtail the reproductive output. The decline of the gastropod *Nucella lapillus* in southwestern England has been related to the use of TBT by measurement of the frequency of male pseudogenitalia in field populations (Bryan et al., 1986).

■ **The effects of toxic substances on single species may be measured by constructing models relating toxic substance concentration to population growth.**

Effects of toxic substances at the single organism level can be used to predict the fate of populations exposed to pollution. In order to do this, one must be able to estimate the relationship of concentration of a toxic substance to growth, survival, and reproductive output. The life cycle is divided into life-history stages, and then each stage is assayed for survival and reproductive output, when appropriate, from one stage to the next. This approach is analogous to the age-specific approach to population modeling discussed in Chapter 21 in a fisheries context. For example, Diane Nacci and colleagues (2002b) examined the effects of PCBs and dioxins, two toxic substances found in high concentrations in New Bedford Harbor, Massachusetts, and measured the effects on survival and reproduction in the nonmigratory killifish *Fundulus heteroclitus*. Using laboratory data, they predicted significant effects on population growth from exposure to a range of concentrations of the toxic substances (**Figure 22.1**).

■ **The introduction of toxic substances may be related to uptake by individuals in field populations.**

Exposure of living organisms to waterborne and sediment-associated toxic substances often results in biological uptake. The concentration of a toxic substance in an animal at any one time is a function of the environmental concentration of the substance, the biological uptake rate, and the rate of release. Physiological models of uptake and release must include an accurate measure of environmental exposure, uptake and maintenance within various parts of the body, and rates of release by a variety of cellular and exchange methods such as release by excretory organs and gills into the environment. Wang and Fisher (1998) examined uptake and release of metals by copepods and found that processing time was very rapid and metals stayed in a copepod's body only a few days at the most. Zinc and selenium were taken up mainly in the food, but silver, cobalt, and cadmium were taken up from dissolved sources in the water. Benthic animals living within the sediment also derive toxics directly by ingesting sediment but also take up substances from the pore waters.

■ **Gene expression may be an effective means of assaying for effects of toxins.**

When an organism is exposed to a toxic substance, a number of genes are induced to express a wide range of defense mechanisms or physiological responses. The degree of expression of genes sensitive to cellular uptake of toxic substances is a very sensitive measure of environmental

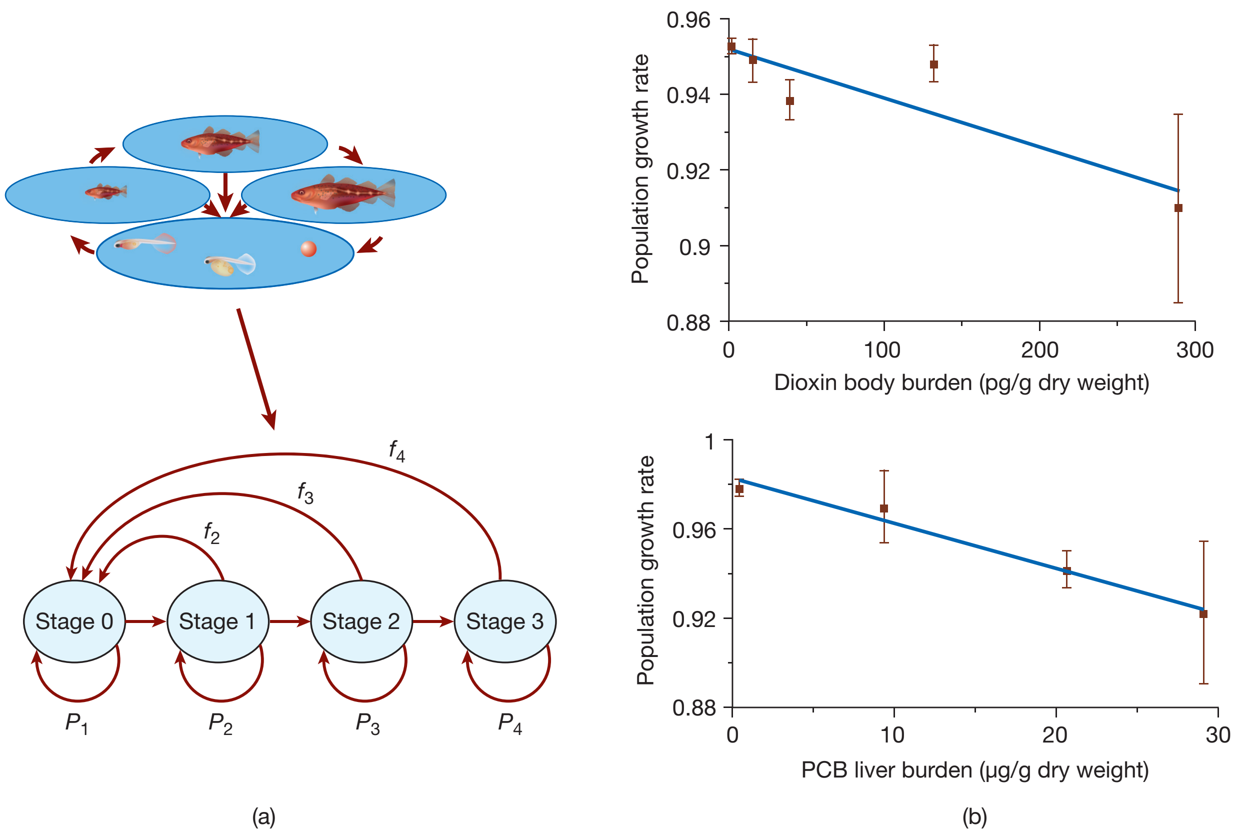


FIG. 22.1 (a) Diagram of a model used to calculate population growth of the killifish *Fundulus heteroclitus*, using four life-history stages (stage 0 is immature; stages 1, 2, and 3 can reproduce). A population projection can be made with the knowledge of stage-specific survival (*P*); reproductive rate (*f*) of stages 1, 2, and 3; and development from one stage into another. (b) Use of data on survival and reproduction to make population rate projections as a function of dioxin and PCB concentrations on the killifish *Fundulus heteroclitus*. (Modified from Nacci et al., 2002b)

exposure.[1] For example, fish are commonly exposed in urbanized estuaries to aromatic hydrocarbons, including dioxins and PCBs. Responses involve arylhydrocarbon receptor (AHR) signaling pathways, and exposure to dioxins and other substances involves increased expression of the *CYP1A* gene, which has been used as a measure of pollutant exposure. AHR signaling and toxicity involve passage of the AHR–dioxin complex into the nucleus. Some metals, such as copper, cadmium, and mercury, are bound and detoxified by metallothionein, a small protein that is rich in metal-binding cysteine amino acid residues. In some cases, increased metals directly induce expression of metallothionein genes, and measures of mRNAs for this protein would be a good assay of pollution exposure. Alternatively, a proteomic approach would estimate the cellular concentration of metallothionein proteins. Also, different genotypes can be shown to produce proteins with differential binding to toxics.

When an organism is exposed to a toxic substance, expression by more than one gene will occur, and complex interactions of gene expression will be employed to allow the organism to respond to the exposure. Studies of multiple gene expression to toxic substances are likely to be complex. **Microarray** techniques are used to develop a DNA sequence library. DNA sequences are synthesized and usually placed on chips. After exposure to a toxic substance, messenger RNA of an organism is isolated and exposed to the chips, and a coupling mechanism to a fluorescent protein system allows a visualization of the expression of multiple genes (**Figure 22.2**). There are two objectives of looking at the responses of groups of genes. First, it would be useful to discover suites of functionally related genes that interact and respond to pollutants. Second, researchers hope to be able to use responses of given suites of genes as indicators of stress by particular pollutants. For example, Venier and colleagues (2006) developed unique sequences for about 1,700 distinct DNA probes in the mussel *Mytilus galloprovincialis* and exposed these mussels in the laboratory to metals and organic toxic substances. They found differences in gene expression and were able to relate these to field-caught mussels in the Bay of Venice, Italy.

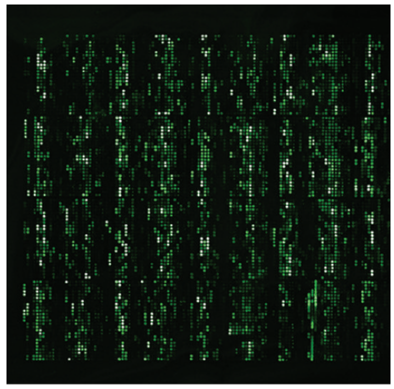


FIG. 22.2 Gene expression of a large array of genes of the mussel *Mytilus edulis* when exposed to metals, as shown by a microarray. Each dot represents a sequence on a standard microarray chip, which consists of part of the sequence of DNA of a functioning gene that might prove to be involved in responses to metals. The sequences may or may not bind to messenger RNA sequences from the exposed mussel, which are the result of gene expression (transcription of the gene into mRNAs). Darker green signifies more gene expression for a given sequence type. By analyzing the degrees of expression, the groups of genes that respond to cadmium exposure can be determined, which allows an understanding of the network of genes involved in responses to toxic substances. (Courtesy of Robert Chapman)

■ With genetic variation in natural populations and differences in fitness among genotypes, evolution of resistance to toxic substances may occur.

The introduction of a toxic substance may kill off only a fraction of a species population. If there is genetic variability for resistance to the toxic substance, then the population may evolve resistance. After a period of time, the average individual will not be sensitive to the toxic substance. The degree of resistance can, therefore, be used as an index of the biological effect of a substance introduced by human beings. Klerks and Levinton (1989) investigated a population of oligochaetes that had lived exposed to high concentrations of cadmium in the sediment. Worms from a polluted site survived well when exposed to cadmium-rich sediments, but worms taken from a clean area mostly died when exposed to the same sediments. The ability to survive the cadmium was controlled by genetic variation (**Figure 22.3**). New Bedford Harbor, Massachusetts, is very polluted with toxic PCBs and other substances and should be a location of strong potential natural selection for resistance to toxic substances. New Bedford Harbor killifish had much higher expression of P450 genes than fish from a nearby unpolluted river, suggesting that natural selection had caused the difference (Greytak et al., 2005). Diane Nacci and colleagues (2002a, 2002b) did crossing experiments and demonstrated that resistance of killifish to dioxin-like compounds was genetically based, and that killifish populations were more resistant in areas of New Bedford Harbor where concentrations of PCBs (**Figure 22.4**) and dioxin-like compounds were higher. Resistant genotypes were found in a wide range of New Bedford Harbor habitats, far wider than had been declared to be toxic by the U.S. Environmental Protection Agency.

A molecular mechanism has been found for resistance to PCBs (see later in this chapter for discussion of pollution sources and toxicity of PCBs) of the Hudson River population of the Atlantic tomcod *Microgadus tomcod*. Hudson River tomcod are widely known because of the high occurrence of cancers and skin lesions, an apparent response to toxins in the water. A genetic variant of the AHR protein was commonly found in Hudson River populations but rarely in other less polluted sites. This protein defeats the binding to PCB 126, which is a PCB variant that is toxic to fish. Apparently, rapid natural selection had selected this rare variant, relative to the common one found in most other populations along the northeast coast of the United States and Canada (Wirgin et al., 2011).

[1] See bonus chapter "Molecular Tool for Marine Biology," online.

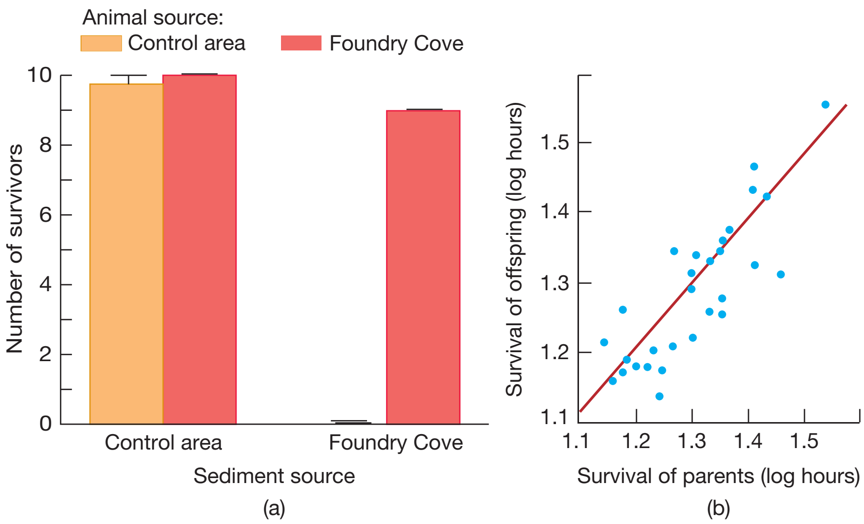


FIG. 22.3 (a) The aquatic oligochaete *Limnodrilus hoffmeisteri*, taken from a highly cadmium-polluted cove, had much greater resistance to cadmium than worms from an unpolluted control area. Its survival was nearly the same in metal-polluted sediment as in clean sediment, whereas the worms from the unpolluted habitat soon died when exposed to the metal-polluted sediments. (b) The correlation of resistance to cadmium between parents and offspring indicates a strong genetic component to the resistance trait. (After Klerks and Levinton, 1989, 1992)

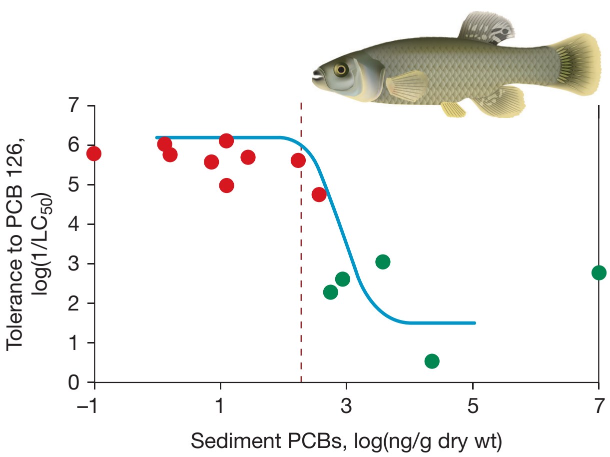


FIG. 22.4 Tolerance for polychlorinated biphenyls (PCB 126) of the nonmigratory killifish *Fundulus heteroclitus* when taken from a range of contaminated areas with different PCB concentrations from New Jersey and Massachusetts, as measured by the reciprocal of LC_{50} after exposure to a given concentration. Low values indicate the fish are more tolerant of PCBs. Green dots signify highly contaminated sites. (After Nacci et al., 2002a)

Measuring Effects on Community Function

■ **Many toxic substances are transferred from one trophic level to the next as predators consume prey.**

Organisms may take up toxic substances by feeding on other species, resulting in **trophic transfer**. Some metals, for example, remain in the cytosol, while others become associated with cell membranes and might even be deposited in shells and skeletons. Clearly, the latter will not be as efficiently transferred as toxic substances that remain in the cytosol. William Wallace and Glenn Lopez (1997) found that cadmium was bound to metal-binding proteins in the oligochaete worm *Limnodrilus hoffmeisteri*. They fed these worms to predatory shrimp and found that trophic transfer was directly correlated with the cadmium that was bound to the metal-binding proteins in the cytosol. Cadmium bound to the cell membrane was not very efficiently transferred to the predator. Cadmium taken up by the shrimp impaired their ability to successfully attack prey.

■ **Some toxic substances are magnified in concentration in organisms, as the toxin is transferred through the food web.**

Many substances taken up by marine organisms undergo **bioconcentration**, where a substance is taken up from the water directly and is concentrated within the tissues. In some cases, **biomagnification** *increases the concentration of a toxic substance in the tissues as it moves from one trophic level to the next*. A classic case is bird consumption of fish and invertebrate predators contaminated with DDT. DDT is soluble in fat and concentrates in the birds, relative to prey items. However, DDT is usually not biomagnified in other parts of the food web. Methylmercury is usually biomagnified as it moves from animal prey to predator. Methylmercury is also bioconcentrated by large fish (owing to the relatively low loss rate), so large-bodied tuna have relatively high concentrations of methylmercury. In fact, frequent sushi consumers occasionally suffer mercury poisoning, which can cause tremors, impaired vision, and severe neurological damage.

■ **When a marine organism is exposed to a toxic substance, the toxic substance may not increase in concentration in the body, or it may indeed continue to increase.**

The biological uptake pattern may also differ among species. **Noncumulative toxic substances** do not increase in concentration in the body over time, even if the organism is exposed chronically to the substance. In this case, the organism has an efficient removal mechanism for the toxic substance. By contrast, **cumulative toxic substances** continue to increase in concentration and may be found most abundantly in a single tissue. For example, cadmium tends to increase over time in the digestive gland of crabs. Cumulative uptake occurs only if there is a **specific biological mechanism of tissue concentration** and a **low loss rate** of the toxic substance from the body.

Measuring Effects on Biodiversity

Diversity is said to increase if the number of species increases, or if the abundances of the species are more evenly distributed (see Chapter 20). For example, a low-diversity habitat would consist of very few species, with strong dominance by one species. Although one can clearly find exceptions, diversity tends to decline in strongly polluted habitats (**Figure 22.5**).

Species resistant to pollution are often a small subset of the total species pool that includes species capable of rapid colonization in strongly disturbed habitats; such species are termed **opportunists**. Marine communities subject to pollution often resemble natural assemblages strongly affected by physical disturbance factors. While diversity can be monitored to assess pollution, usually the effects of pollution can be detected with much more sensitivity by using statistical approaches to measure species abundance changes and patterns of association among species. In all cases, it is essential to compare species assemblages in polluted habitats with unpolluted habitats that are otherwise similar in substratum, depth, current strength, and so on. It is also preferable to have data on species occurrences before the impact occurred, to compare to impacted sites and nearby control sites that have not been impacted.

Toxic Substances

Toxic Metals

■ **Metals are often cumulative toxins and have strong effects when consumed by human beings.**

For thousands of years, metals have been released by human industry into the marine environment. Mining is a major source of metals, and mines near estuaries have been a major source of pollution. A wide variety of industrial processes release metals. For example, before regulatory efforts, mercury was released: In emissions from wood pulp processing; as aerosols from coal-burning power plants; to the atmosphere from burning of trash; and in river and atmospheric sources from mercury mines. Metals also are found in great quantities in sewage; in urban areas, this is probably the single greatest source of metal pollution. In agricultural areas, metals are sometimes released as components of insecticides and fungicides. Mercury and copper have been components of antifouling paints, and the toxic effects of tributyltin are recognized widely.

Although the effects of metals on human beings have been studied extensively, relatively little is known about the specific physiological effects on marine organisms. Metals such as zinc and copper are known to denature many proteins and are therefore fundamental poisons. Copper also may bind to blood pigments and impair their function. Many metals are known to increase mortality in a wide variety of species.

Marine organisms produce metal-binding proteins, such as metallothionein, which bind to metals to allow their deposition within cell organelles as **metal-rich granules** in chemically less reactive forms that aid in reducing the exposure of cell constituents to chemical reactions with metals.

Mercury is probably the most notoriously toxic metal. Mercury comes from a number of sources, including atmospheric deposition from often far-distant coal-burning

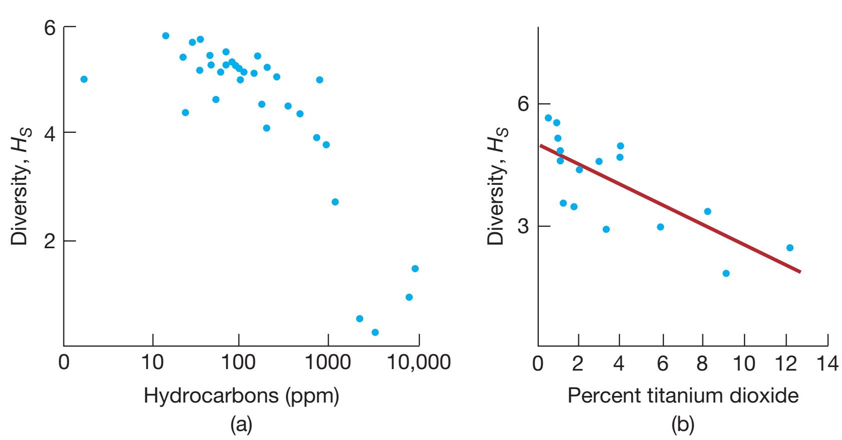


FIG. 22.5 Reduction of diversity of benthic macrofauna (a) along a gradient of increasing sediment hydrocarbon concentration near an oil platform and (b) with increasing concentration of titanium dioxide waste in a Norwegian fjord. H_S is a measure of diversity that increases with the number of species and the relative evenness of abundance of the species. (After Gray, 1989)

power plants, burning of waste materials, industrial sources in factory outfall pipes, mines, and sewage. It is particularly toxic when attached to a short-carbon-chain alkyl group in the form of **methylmercury**. Mercury may be deposited originally in metallic form, but it will be converted into methylmercury when it enters an estuary or a coastal waterway and is exposed to sediments and microbial activity in a bacterially mediated process known as methylation. We do not know enough about the exact microbial mechanism of methylation. Recent evidence suggests the necessity of activity of two genes, *hgcA* and *hgcB*, in the bacteria *Desulfovibrio desulfuricans* and *Geobacter sulfurreducens* (Parks et al., 2013). It is possible that there are other mechanisms of methylation in marine waters and bottom sediments.

The principal effect of methylmercury on human beings is strong disruption of nervous function, especially in the fetus. The odd behavior of the Mad Hatter in *Alice in Wonderland* constitutes an allusion, which would have been obvious to Lewis Carroll's contemporaries, to the effects of the mercury poisoning that was so common among hat makers in mid-nineteenth-century England. In Minamata, Japan, the industrial release of mercury, which was absorbed by fishes and shellfish, led to large outbreaks of nervous disorders and deaths from the 1950s to the 1970s. Unfortunately, mercury passes across the placenta, and many women who had eaten mercury-laden fish bore children who had the affliction that came to be known as Minamata disease. Some other coastal populations have been affected in much the same way. Mercury is also known to cause myocardial infarctions. Mercury in sushi can be a source of toxicity in avid consumers.

One important pathway for mercury to reach human consumers is as follows: atmospheric mercury deposition to watersheds → entry into watershed soil and sediments → dissolved methylmercury in water → methylmercury in fish through a bioaccumulation factor from prey in water → and human consumption of fish. In San Francisco Bay, a considerable amount of mercury arrives from the watershed because of rock formations with high mercury concentrations and also from leakage from mining activities. Mostly because of atmospheric deposition and industrial point sources, there are many hotspots of high mercury concentrations in fish throughout the world. In the Hudson River, anglers who eat locally caught fish have higher tissue mercury concentrations than the rest of the human population. We mentioned earlier in the chapter that methylmercury is biomagnified up the food chain to large carnivores such as tuna. In the past few decades, inputs of mercury from some sources such as burning of wastes have declined. Levinton and Pochron (2008) found that mercury concentrations in five common fish species have declined steadily in the Hudson River since the 1970s. The decline is probably a response to regional regulations that reduced Hg inputs into the local environment. But there is a worry that the need for worldwide energy will result in more burning of coal, which will increase the inputs of mercury into the atmosphere. Such increases are widespread in India and China.

Most mercury exposure to people in the United States is due to consumption of oceanic fish such as various species of tuna, swordfish, and pollock. It is possible that mercury in oceanic fishes, such as North Pacific tuna, is converted to the methylmercury form in open ocean waters. Mercury might be associated with particulate carbon, which sinks through the water column and is methylated by microorganisms during consumption of the POC. This may cause an increase of mercury exposure in the future, as mercury-bearing coal is burned at higher rates in east and south Asia (Sunderland et al., 2009). Mercury has been found in toxic concentrations in the Arctic Ocean in beluga and narwhal, which are hunted by native peoples of Greenland and Canada.

Cadmium is another fairly common metal, although the distribution of its sources is often more variable than is the case for mercury. Cadmium may enter in sewage, but it also comes from outfalls in electroplating factories and battery manufacturing plants. In Foundry Cove, a bay adjacent to the Hudson River estuary, a battery factory outfall caused cadmium concentrations in bottom sediments to be in the range of 1–25 percent! The most notable toxic effect on human beings is on kidney function, but larger accumulations can lead to bone deformities and severe pain. Consumption of cadmium-laden sea turtles and dugongs in northern Australia has had apparent negative effects on kidney function in residents of the Torres Strait. Cadmium is found to be concentrated in rice in certain areas in Japan, but crabs and shellfish also are contaminated. At present, cadmium is highly concentrated in blue crabs in the Hudson River, and frequent crab consumption will produce pathological renal effects. Cadmium has also been found to severely affect eels by impairing lipid accumulation, gamete production, and migration (Pierron et al., 2008), and it may have contributed to the decline, along with overfishing, of the American and European eels in recent decades.

The badly contaminated Foundry Cove of the Hudson River is remarkable for the fact that benthic animals were dense there, despite common sediment cadmium concentrations of 10,000 ppm. The oligochaete *Limnodrilus hoffmeisteri* apparently evolved a resistance to high concentrations of cadmium (**Figure 22.3**). Individuals of this species from other areas died soon after being introduced into Foundry Cove sediments, whereas indigenous worms survived well (Klerks and Levinton, 1989). The resistance is genetically based and may be related to the higher production of a metal-binding protein and the ability to precipitate cadmium sulfide in intracellular organelles. The cove was cleaned up partially in 1994, and local populations lost their resistance in just nine generations. After the cleanup, invasion of nonresistant genotypes from outside the cove probably changed the genetic makeup of the worm population (Levinton et al., 2003).

Lead was used during Roman times in water pipes, pottery, and coins. Since the industrial era, lead has been used extensively in lead storage batteries and paints, and as an additive to motor fuels. Lead is also found in fossil fuels and is therefore emitted during burning in power plants. Lead is most common as an air pollutant, and there has been a movement in recent years to reduce lead in internal combustion engine fuels. The action is the result of knowledge of the strongly toxic effects of lead on the nervous system, and especially on the neurological development of young children.

Lead is now found in relatively high concentrations in estuarine and marine sediments adjacent to urban areas. The most probable sources are release from industrial pipes, dissolution from lead pipe systems, atmospheric deposition, washout of gasoline-ridden wastewater into storm sewers, direct disposal of fuels into seawater, and sewage release.

While other toxic substances are also monitored, metals are a prime target for study in the Mussel Watch Program (an international monitoring study that analyzes mussels in coastal habitats on both sides of the Atlantic). Mussels are analyzed for a variety of metals to judge whether bioavailable toxic substances are entering coastal marine ecosystems. Owing to the differences in chemistry among metals, an increase of concentration must be interpreted carefully.

Pesticides

■ **Pesticides are usually designed to kill terrestrial insects, but they are washed into coastal waters and are often toxic to marine life.**

Pesticides include a wide variety of compounds used typically to kill insects harmful to crops. Because of the large spatial scale of pest infestations, most pesticides are applied in large amounts (nearly 1 billion kg per year in the United States) and in great variety (there are about 1,000 different types). Although some pesticides are very effective, most target species have sufficient genetic variability of resistance to rapidly evolve resistance. At first, the frequency of resistant variants may be very low, but unlike nonresistant individuals, the resistant individuals will survive and reproduce. The evolution of resistance has tended to magnify both the toxicity and the variety of pesticide deployment. Despite this arms race, the insects have been winning by and large, and crop damage has steadily increased over the last few decades. Herbicides are effective in killing undesirable plants, but they also are potentially toxic to human beings.

There is not enough space here to describe the variety of pesticides in any detail, but several have been extremely harmful to marine organisms. To assess the potential harm of a pesticide, the solubility and chemical characteristics related to mobility, toxicity, and rate of degradation must be known. Substances that are easily mobilized in runoff have generally toxic effects in many organisms, and those that are slow to degrade are liable to be the most dangerous.

Chlorinated hydrocarbons (DDT, dieldrin, chlordane) have the most dangerous combination of harmful properties. DDT's degradation rate is on the order of years, and it washes readily from salt marshes into adjacent shallow estuarine and marine bottoms. **DDT** (**Figure 22.6**) was used widely as a means of eliminating the *Anopheles* mosquito, which carries malaria. It was later used as a general insecticide on many crops. In the 1960s, the general decline of a large number of seabird and terrestrial predatory species was noticed, especially those at the top of food chains, such as the bald eagle, peregrine falcon, the Bermuda petrel, the brown pelican, and the osprey. DDT and a few related compounds, which are very soluble in fat, were magnified up the food chain to those top predators that ate large numbers of contaminated fishes. DDT and related residues disrupt reproduction and especially eggshell construction, to the degree that shells became too thin to permit normal egg development. Many species declined catastrophically until widespread bans on DDT use were imposed by Western industrialized nations. In recent years, DDT has degraded in the U.S. marine environment. Peregrine falcons, osprey, and bald eagles have all recovered strongly. DDT is no longer used in a number of developed countries but continues to be used to a lesser degree in developing tropical countries because of its continuing effectiveness in dealing with malaria.

Many of the pesticides directed at insects are also toxic to their arthropodan relatives, the crustaceans. Spraying of insecticide on coastal agricultural areas and on marshes for mosquito control may therefore have unfortunate consequences. The spraying of the insecticide kepone caused the closure of the James River (Chesapeake Bay watershed) to fishing and devastated the blue crab population. Other insecticides, such as mirex, harm crabs, especially during larval development. Even when marine invertebrate populations are not affected, they may sequester the toxins, which may pose a danger to human beings. Dioxin, for example, is a

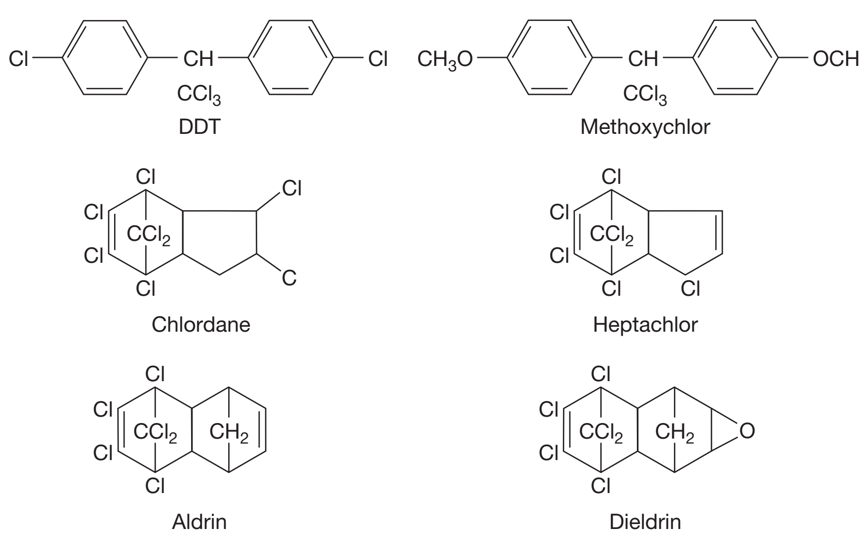


FIG. 22.6 DDT and related compounds.

contaminant derivative of some herbicides and is believed to be carcinogenic to people. There have been reports of dioxin in fish and shellfish. Dioxin in the sediment interferes with the reproductive cycle of estuarine fish. The larvicide methoprene is a juvenile hormone mimic that kills *Aedes* mosquito larvae but also strongly affects development of larval stages of estuarine crabs (Christiansen et al., 1977).

Glyphosate is a major component of a variety of herbicides used to control weeds and even invasive plants such as *Spartina* marsh grass species; as a result, glyphosate is found widespread in estuarine environments. It is not yet clear whether there are strong impacts of glyphosate on marine life. Experiments with transcriptomic responses by juvenile oysters demonstrate the moderate increase of gene expression of several candidate response genes such as catalases (Mottier et al., 2014) but no major effects on oyster condition. Effects on larvae and embryos were similarly modest. Direct applications of herbicides with glyphosate are harmful to target organisms such as sprayed invasive *Spartina* but also to seaweeds that might be present.

PCBs

- **Polychlorinated biphenyls (PCBs) derive from industrial activities and have proven to pose a major toxicity problem in estuarine environments.**

Polychlorinated biphenyls are a class of compounds that have been used extensively as lubricants in various types of industrial machinery. Throughout the world, PCBs have been released into coastal waters and have been found as a contaminant of invertebrates, fishes, and marine mammals. PCBs cause carcinomas in mice and are therefore thought to be a danger to human beings. These substances are particularly a problem because of their very high toxicity and chemical stability. Although marine bacteria can degrade them, the process is very slow.

PCBs have been discovered in a wide variety of commercially captured fishes, such as bluefish and striped bass in the New York and southern New England region. They have been implicated in reproductive failures and reduced populations of seals in the North Sea–Baltic Sea regions. A release of PCBs in the Hudson River from a General Electric Corporation facility resulted in high loads of PCBs in sediments, the contamination of fishes, and the shutdown of the striped bass fishery within the Hudson and even in adjacent waters for a few years. The substances have also turned up in fish caught by Native Americans in Alaska, perhaps owing to exposure of fishes that spawned in industrially polluted rivers in the former Soviet Union. It is not clear whether the fishes take up PCBs primarily from contaminated prey or directly from solution.

In the United States, two large Superfund sites have been declared on the basis of PCB concentration, one in New Bedford Harbor, Massachusetts, and another in the Hudson River Estuary, the largest Superfund site in the country. A plan for dredging the New Bedford Harbor site is already completed, and the Hudson River site dredging and capping has been completed, although many complain that significant PCB sediment areas remain to be dredged.

Plastics

- **Plastic products and debris enter the ocean from garbage dumps, storm impacts on the shore, and many other sources. The material accumulates in low current areas and breaks down into small pieces that are ingested by a wide variety of marine organisms.**

Approximately 200 million tons of plastic products are produced annually worldwide, and a significant fraction—possibly 10 percent—enters the ocean from oceangoing ships, from dumps near the coastal zone, and from other sources. Oceanic circulation moves material great distances. For example, an enormous region of the central north Pacific has accumulated thousands of square kilometers of plastic-laden surface water. When fresh, this material can entangle mammals and fish (**Figure 22.7**).

Material starting as bags, shoes, toothbrushes, and other products breaks down and is eroded into small particles that enter into biological systems. In surface waters, plastic debris is ingested by fish, seabirds, and sea turtles. An investigation of albatrosses found plastics in 30 of 47 birds, or about 64 percent, recovered as bycatch. Plastics are also found in egested material fed to seabird chicks on nesting grounds (Gray et al., 2012). Plastics also entangle a wide variety of marine organisms. A number of toxic substances, such as PCBs, sorb onto plastic surfaces, making the plastic debris a possible major source of toxicity (Engler, 2012).

Plastics enter the marine environment and immediately become part of the marine ecosystem (**Figure 22.8**): They are transported by currents, deposited on the sea floor, eaten by marine creatures, and even then consumed and transferred through marine food webs. Microplastic particles (plastic particles < 5 mm in size) are now widespread in hand and facial cleansers. They may remain suspended in the water column, where they are ingested by marine suspension feeders or wind up in sediments, eaten by deposit feeders. An investigation near the Great Barrier Reef demonstrated that corals appear to detect plastic particles as prey and ingest as much mass of plastic particles as they ingest of live plankton prey (Hall et al., 2015). The high surface area of the plastic microspheres attracts a number of chemical moieties but especially various metals and organic chemicals such as PCBs that are often toxic. So the question is open: Are microplastics toxic to any degree? If they are, this is a major calamity given the worldwide occurrence.

So far the evidence is very incomplete, and I hope that students can see that this is an area in which more progress in research is needed. For example, a study by Nobre and colleagues (2015) demonstrated that materials leached from microplastic particles appear to cause anomalous development of sea urchin larvae. New plastic pellets appear to be far more toxic than those recovered from a beach, so some of the toxic substances that adsorb to plastic particles may degrade over time, making the plastic particles less effective as vectors of adsorbed toxins. An isopod collected from the North Sea was fed microplastic spheres embedded in food, and no negative effects were found on digestive

FIG. 22.7 Divers free a plastic-entangled Hawaiian monk seal in the northwest Hawaiian Islands. They were successful. (Photograph by Ray Boland, with permission from NOAA)

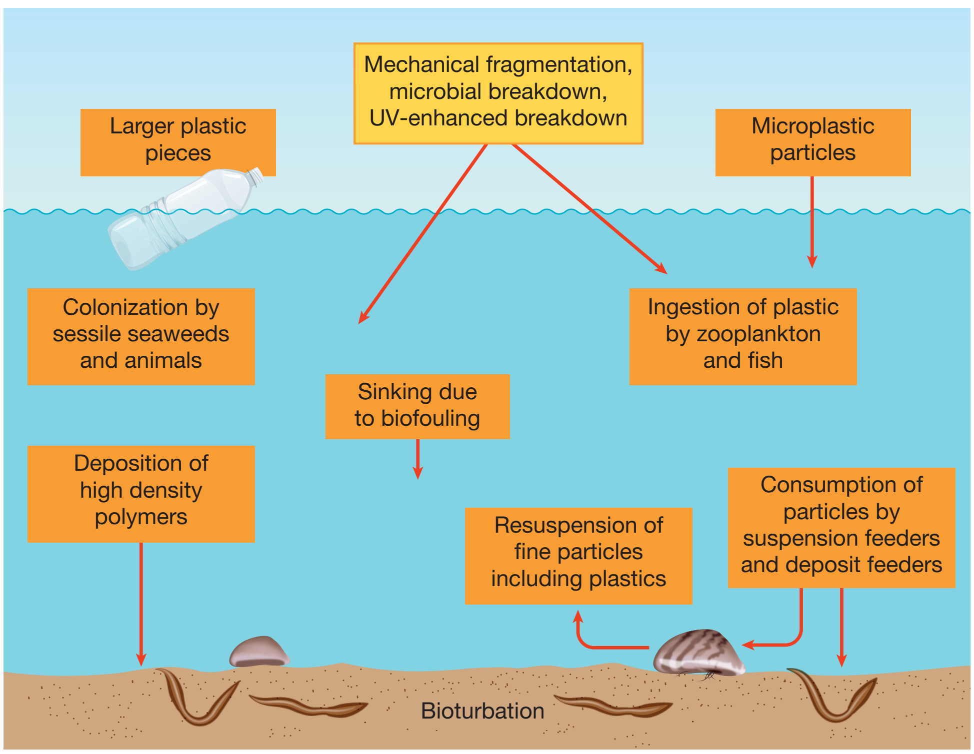


FIG. 22.8 Pathways for the transport of plastics through the ocean and its food webs. (After Wright et al. 2013)

organs, survival, or molting frequency. On the other hand, microplastic spheres were filtered by mussels and taken up and engulfed by cells, and there were clear negative cytological effects (von Moos et al., 2012).

When the Pacific oyster *Crassostrea gigas* (a major species used in aquaculture throughout the world) was fed fresh plastic nanoparticles of about 6 μm, used in facial cleansers, a number of strongly negative effects followed, including reduced oocyte development, sperm velocity, larval survival, and development rate (Sussarellu et al., 2016). This study also gave us great insight on the oyster's responses by following gene expression in the transcriptome. By examining different classes of genes responsible for different reproductive and maintenance functions, it was possible to see a shift of plastic-stressed oysters from reproductive to metabolic activities associated with growth. Apparently the oysters were "interpreting" the presence of the plastic particles as a major stress, which resulted in a shift from reproductive activities to maintenance of the body, in order to maintain survival.

Oil Pollution

■ **Oil pollution can have both short-term and long-lasting effects on communities and individual species.**

In the past 50 years, oil pollution has become a major problem in the coastal zone. Drilling, transport, and burning have all added oil to marine environments. The following are the major sources of oil pollution: (1) leaks from and breakup of oil tankers and barges, (2) leaks from wells drilled offshore, (3) leaks from marine terminals and in harbors, and (4) washout of oil from settled areas into storm drains and direct washout to the shoreline.

The wreck of the tanker *Torrey Canyon* on rocks off the English coast in 1967 was the first oil spill that awakened the international community to the dangers of oil transport. About 80 tons of crude oil was released and 40 tons burned after the Royal Air Force made a bombing run over the site. Detergents were sprayed onto the sea surface to break up the oil slick. Both the oil and the detergents devastated seabird populations and shore invertebrates. In 1978, the wreck of the tanker *Amoco Cadiz* released about 200,000 tons of oil over more than 300 km of the coast of Brittany, France. The result was devastation to seabirds, soft-bottom benthos, and oyster beds (**Figure 22.9**). Recovery now appears complete. In general, recovery following oil spills takes 2–10 years, but there is strong variation depending on the biological group.

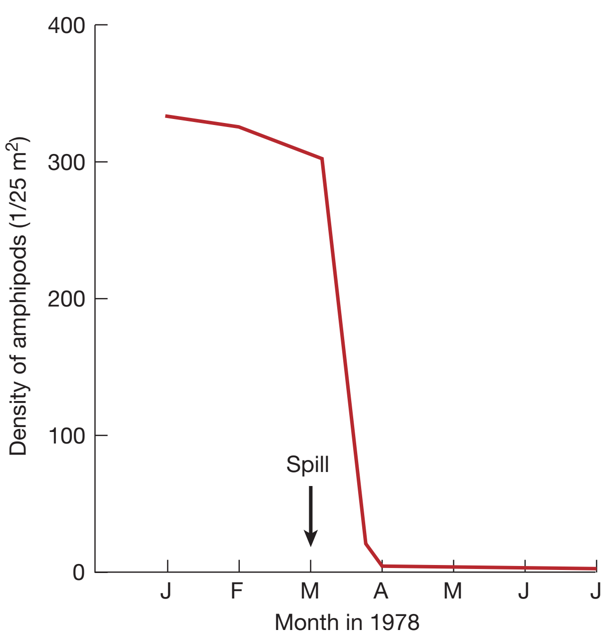


FIG. 22.9 Change in abundance of amphipods in coastal bottom sediments following the wreck of the *Amoco Cadiz* off the coast of Brittany.

In the United States, an accidental leak in 1969 from an offshore well near Santa Barbara, California, affected marine life in the coastal zone. The effects of the spill were not studied adequately, but the spill had great impact on public opinion concerning environmental issues. In the same year, however, a spill from the relatively small barge *Florida* off Cape Cod, Massachusetts, was studied intensively by a team of benthic ecologists and chemists led by Howard Sanders of the Woods Hole Oceanographic Institution (Sanders et al., 1980). This barge carried 14,000 barrels of oil (1 barrel = 159 liters), a quarter of which was spilled in the area of the relatively small Wild Harbor, Massachusetts. Since the load was number 2 diesel fuel oil, the concentration of relatively toxic aromatic hydrocarbons was high, about 41 percent.

The spill strongly affected the benthic community. A diverse community of clams and polychaetes crashed and was replaced by a very few species. In particular, the polychaete *Capitella capitata* came to dominate the intertidal and subtidal soft bottoms. It took several years for the oil to lose most of its effects. Much of the oil was buried, only to spread during winter storms that eroded the covering sediment. Toxic substances, such as aromatic hydrocarbons, were found in shellfish more than 1 year after the spill. This suggested a lingering danger to human beings who might consume the shellfish. Reproduction of shellfish such as mussels was greatly impaired. Oil can still be found in marsh sediments in West Falmouth, and toxic effects on fauna can be detected today.

Major oil tanker spills still occur, but less often. In March 1989, the tanker *Exxon Valdez* hit a reef in Prince William Sound, Alaska, and spilled about 11 million gallons of oil, the worst tanker spill in U.S. history. Thousands of marine mammals and seabirds were killed, and hundreds of miles of shoreline were covered with oil. Because a strong storm developed 2 days after the spill and because the oil was heavy crude (harder to break up), dispersants were not added to the water and most efforts were devoted to cleaning along the shoreline as the oil reached the shore. Acute short-term effects were followed by long-term declines in marine life (Peterson et al., 2003). Toxic substances from the oil had a negative impact on anadromous fish reproduction for several years after the spill. After pilot tests, fertilizer was applied to shorelines to provide nutrition for bacteria that contributed to the breakdown of the oil. Oil from the spill still remains in the area, especially in the form of large lenses of dried oil beneath the sediment surface in a number of beaches. Even Antarctica has not been spared. Also in 1989, an Argentinean tanker capsized and spilled about 200,000 gallons of oil. Thousands of penguins, seals, and seabirds were killed.

Some of the complex effects of oil spills were well studied by scientists at the Smithsonian Tropical Research Institution following a spill in 1986 on the Caribbean side of Panama (**Figure 22.10**). Bahia Las Minas had been surveyed for years before the spill washed oil ashore, which

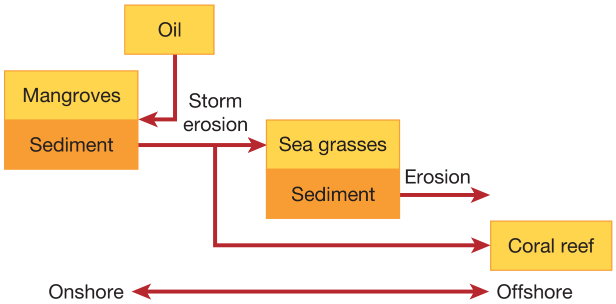


FIG. 22.10 The cascading effects of oil derived from a 1986 spill along the shores of Bahia Las Minas in Panama.

allowed comparisons before and after the spill. Initially the spill destroyed approximately 7 percent of the mangroves on the shoreline. The decay of the mangrove trees caused them to dislodge and roll about the shore, causing damage to the benthos. The oil also damaged sea grass meadows, which caused rhizome mats to disappear. The sediment was no longer held in place: It was transported seaward, which increased the turbidity and sedimentation and reduced the survival of nearby corals. Oil seeped into the mangrove forest sediment, but the rainy season soon came, and storms and freshwater flow caused the oil to be eroded and transported offshore, which caused more damage to sea grasses and corals. Normally, the mangrove ecosystem traps sediment, which helps clarify the water and benefits the nearby coral reefs. The oil spill therefore set off a cascade of ecological effects.

By far, the largest oil releases have come from submarine well drilling. Drilling pipe is extended into a well in the seafloor from a fixed or floating platform. Most platforms are at shelf depths in relatively shallow water, but in recent years, with the aid of submersible drilling units, some platforms have reached much greater depths, of 1,500 m or more. Wells commonly extend thousands of meters downward from the seafloor surface.

A major blowout occurred in 1979 in a Gulf of Mexico oil well at 60 m depth at Ixtoc, about 100 km offshore in Mexico. Drilling muds failed to balance a back pressure, and the well exploded, releasing about 140 million gallons of oil over a period of 10 months until the well was finally sealed. Because of northward-flowing currents and the long time period of the release, oil spread throughout the shelf waters of the western Gulf of Mexico, reaching shore environments of Texas (**Figure 22.11**). Within Texas, large areas of shoreline were covered with oil, but surface booms (floating barriers) were placed to protect estuaries, and the strategy was largely successful. Although isolated areas are still affected, after 2–3 years, it appeared that most areas had recovered from the blowout.

The Gulf of Mexico experienced an even larger oil release starting April 20, 2010, following an explosion at the British Petroleum (BP) Deepwater Horizon Macondo oil well at 1,525 m depth, approximately 70 km southeast of the Louisiana coast. Following the explosion, 11 platform workers died and a blowout preventer installed at the wellhead failed, resulting in a catastrophic release of oil. By July, over 200 million gallons of oil had been released (Tunnell, 2011; also see OSAT, 2011), making the Deepwater Horizon accident the worst in recorded history. This oil was a lighter crude than that spilled from the *Exxon Valdez*: It

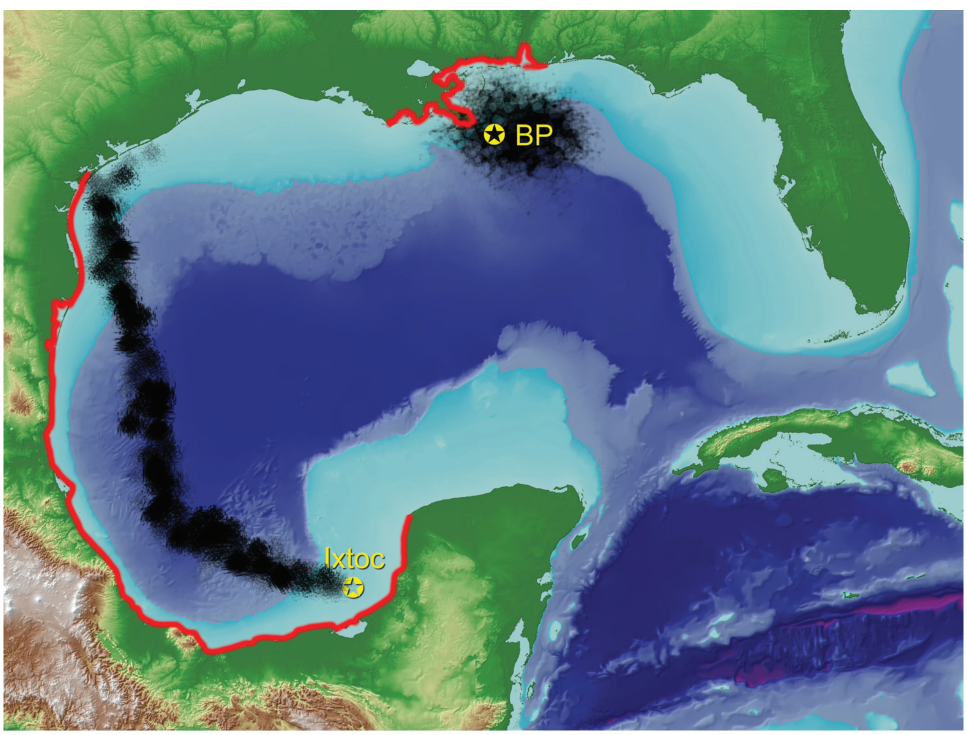


FIG. 22.11 Gulf of Mexico ocean drilling oil blowouts: spread of oil (black area) by currents and extent of the shoreline impacted (red line) from the 1979–1980 Ixtoc well blowout and the 2010 Deepwater Horizon blowout. (Courtesy of I. MacDonald)

contained lower-molecular-mass hydrocarbons, and about half of the hydrocarbons released were methane gas, the remainder being crude oil (King et al., 2015). Thus, the oil was more biodegradable than the oil released in Alaska in 1989. A small minority of the oil was collected from the vicinity of the well. The wellhead was not capped until July 15, 2010, 84 days after the initial event. Toxic drilling muds were also released in the immediate vicinity of the wellhead.

Nearly 2 million gallons of dispersants were added to the water, a large fraction near the wellhead itself. By the beginning of May, the oil reached the Louisiana coast, and authorities used booms to attempt to prevent the oil from reaching shore. The booms were too small and generally failed, however, resulting in concentrated oil-polluted areas in Louisiana. Currents moved the oil to the east and spread as far as Florida, over a period of 3 months. The extent of oil movement and stretch of coastline affected was about 650 km, which was much smaller than the 2,500 km of coast affected during the 10-month spread of the 1979–1980 Ixtoc event in Mexico (**Figure 22.11**).

The coastal environments affected included a large stretch of salt marsh environment. Oil permeated marsh sediments, and a number of seabird and sea turtle nesting grounds were saturated. Marsh sediments impacted with oil killed marsh vegetation, making it likely that such areas will experience erosion in the coming years. Thousands of seabirds and other marine organisms were oiled and killed (see effects of oil on seabirds in next section). Nearly 600 marine mammals, mostly bottlenose dolphins, were found dead ashore, and a few died from an apparent bacterial infection, *Brucella*, that normally afflicts cattle. The longer-term effects for the dolphin are unknown but may involve compromising of the dolphin immune system. While a number of sea turtle eggs were relocated to beaches in Florida, it is likely that most of an entire year class of sea turtles was lost to the Gulf. Economic losses were also severe. About half of the bottlenose dolphins examined showed evidence of direct toxicity from the oil, including lung disease (Schwacke et al., 2014). Most Gulf fisheries off of Louisiana, Mississippi, Alabama, and the panhandle region of Florida were closed for months, although some began reopening in the fall.

Salt marshes in several areas of Louisiana suffered extensive oiling, which led to plant death and erosion. Seaward edges of marshes were oiled more and suffered erosion, which has caused marsh loss. Even 5 years later, storms erode sediments and wash buried oil onto marshes and shores in Louisiana. Such environments already have been lost at a great rate, so the Gulf oil spill represents a stress that mounts on other problems such as low oxygen concentrations and coastal habitat loss. Still, marsh areas where erosion was slight have been recolonized after 2 years by thick marsh grass (Silliman et al., 2012). Oil was found in a restricted set of marshes in Louisiana, but was not detected in most offshore sediments, except within a few kilometers of the well itself, where polycyclic aromatic hydrocarbons (PAHs) and barium concentrations were believed to be toxic to marine organisms.[2] Both macrobenthos and meiobenthos were severely affected within 3 km of the wellhead, but significant effects could also be detected in a larger area around the wellhead of approximately 150 km^2 (Montagna et al., 2013). Recovery may take several decades. In the short term, Alabama coastal juvenile fishes were not affected within important nursery eel grass beds, and some fish stocks are even larger because of the reduced fishery pressure from the fishing closures after the oil spill began (Fodrie and Heck, 2011). Zooplankton dropped during the first summer but returned to normal a year later. Still, there is early evidence that oil hydrocarbons have been incorporated into zooplankton, which might increase through higher levels of the food web. Longer-term effects or even broad areas of sea bottom that might have been affected in the early days after the blowout are essentially unknown, but after a year, widespread evidence shows that the seabed has dense populations of infaunal benthos and sediment bioturbation seems typical, indicating bottom health. An especially exciting part of the story is the question of breakdown of oil by bacteria and the contribution to recovery within the Gulf, which we discuss in **Hot Topics Box 22.1**.

HOT TOPICS IN MARINE BIOLOGY

Is the Gulf of Mexico Adapted to Oil? 22.1

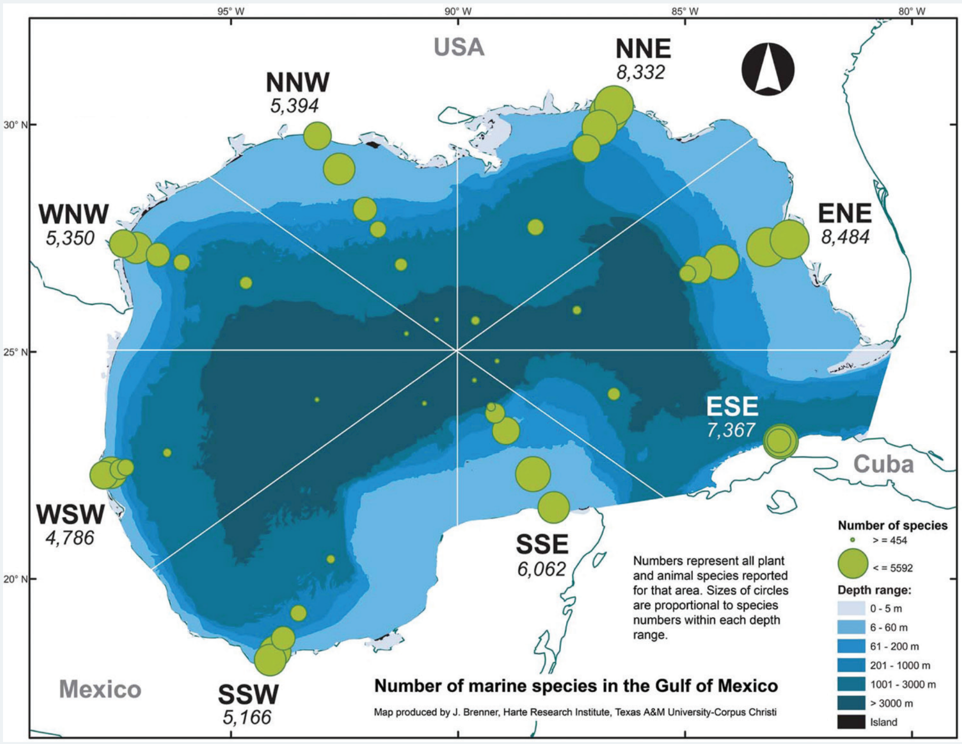
The Deepwater Horizon oil well blowout dumped about 200 million gallons of crude oil into one of most productive inland seas in the world. The Gulf of Mexico ecosystems are among the most diverse in the world, with over 15,000 species. Most of the known diversity is found in depths shallower than 60 m (**Box Figure 22.1**). These shallow areas have much more habitat diversity, which probably explains the increased species diversity. The shallower areas are therefore the most vulnerable with regard to diversity loss. Shoreline habitats harbor crucial seabird nesting areas and fish spawning grounds, which makes it likely that other major Gulf-wide ecosystem effects will be detected following a spill as large as the BP accident. Given the size of the Gulf, it seems unlikely that we will ever get a good estimate of the magnitude of larval, benthic invertebrate, and planktonic mortality caused by the release.

When the well was finally capped in July 2010, many expected the worst: a water body with oil that would persist for years, if not decades. So

[2] Barium in these sediments derive from oil drilling muds.

HOT TOPICS IN MARINE BIOLOGY

Is the Gulf of Mexico Adapted to Oil? *continued* 22.1



BOX FIG. 22.1 Number of marine species in the Gulf of Mexico as a function of depth. (Courtesy of Harte Research Institute)

it came as a surprise that the volume of oil in the Gulf of Mexico following the BP spill appeared to have been reduced to very low levels in only a matter of months! Some oil was trapped in booms along the shoreline and removed at the wellhead to tankers, but underwater plumes of oil were soon discovered, so not all of the oil was even at the surface to be scooped up or destroyed by surfactants, which were liberally sprayed on the surface from airplanes. Indeed, the National Oceanic and Atmospheric Administration can account for about 25 percent of the total oil as being recovered or burned, so most oil has entered the system in a variety of ways.

Where did the oil go? A previous oil well blowout in Mexico in 1979 resulted in the release of 140 million gallons of oil and, although longer-term data are largely anecdotal, short-term studies in the first 3 years showed that Texas shoreline habitats and biotas seemed to recover rapidly and persistent effects remained only in some isolated Mexican localities. Is there a pattern here?

The Deepwater Horizon well explosion occurred in April 2010, but by the following winter, officials from the U.S. Coast Guard and the National Oceanographic and Atmospheric Administration claimed that most of the oil was gone! This was a great surprise to the scientific community and to the public, who greeted the claim with a measure of appropriate skepticism. But some interesting facts about the oil distribution raised some questions. A December 2010 report from the Operational Science Advisory Team (OSAT), chartered by the U.S. Coast Guard, showed that oil was largely absent in Gulf sediments, with the exception of sites within a few kilometers of the Deepwater Horizon wellhead and some shoreline locations. Extensive sampling failed to find concentrations of oil that exceeded concentrations of oil or hydrocarbons that might endanger human health. Most important, any samples with oil did not bear the chemical signature of oil from Deepwater Horizon (Operational Science Advisory Team, 2010). As a result, federal agencies announced that more than three-quarters of the oil was gone by the fall of 2010, owing to cleanups and microbial breakdown. PAHs have been found in sediments within a few kilometers of the wellhead, but a recent report suggests that a year later, we have bottom sediments that are burrowed and show no strong evidence of oiled and anoxic sediments. Does this indicate a recovery? Still, a massive underwater plume of hydrocarbons over 35 km long and 1,000 m deep was reported in June. Are these plumes common, and will they disappear over time?

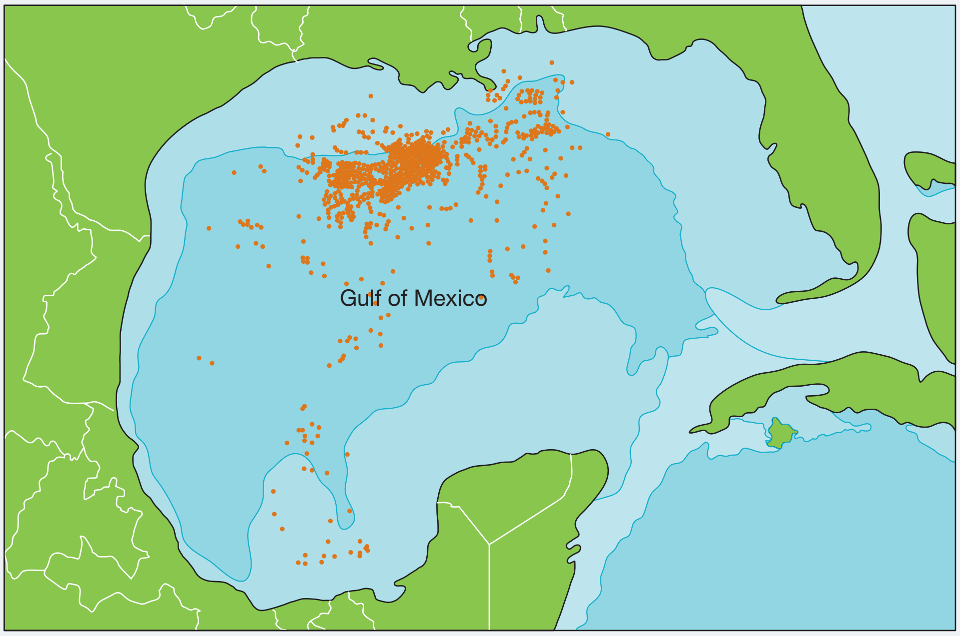
Keep in mind that hydrocarbons have been found in plankton and benthic organisms. Bottlenose dolphins show the effects of oil toxicity. Oil has affected corals but only at sites close to the wellhead. But we are seeing only short-term effects on bottom communities and offshore water column species and apparent recovery. Why? Is it just dilution of oil hydrocarbons?

One possible clue to an important component of the apparent "recovery" can be found in the widespread natural seeps of hydrocarbons that are known throughout the Gulf of Mexico, amounting to a surprising 43 million gallons a year. Most of the known seeps are deeper than the 60 m depth boundary and are found in the central northern part of the Gulf,

continues

HOT TOPICS IN MARINE BIOLOGY

Is the Gulf of Mexico Adapted to Oil? *continued* 22.1



BOX FIG. 22.2 Distribution of known natural hydrocarbon seeps in the Gulf of Mexico. (Courtesy of Ian MacDonald, after Tunnell, 2011)

many near Louisiana and east Texas (**Box Figure 22.2**). In Chapter 18 we discussed the cold-water hydrocarbon seeps that support local hotspots of benthic diversity, resembling the faunas seen around mid-oceanic hot vents. Natural seeps of oil are very common in the Gulf, so we might expect that microbial organisms have appeared and evolved to break down and derive nutrition from the oil and especially methane gas, which can be broken down by specialized bacteria. If oil seepage suddenly increased, then oil-decomposing bacteria might reproduce rapidly and keep up with oil seepage. Keep in mind, however, that the oil spill added hydrocarbons at seven times the background seep rate from the Gulf, so bacteria may not be powerful enough to keep up with biodegradation.

A second important factor is water temperature: Microbial oil-decomposing activity might be faster in the Gulf than in the colder waters of Alaska, although we should note that the Deepwater Horizon well was about 1,500 m deep, where waters were only about 5°C. Still, currents may have spread the hydrocarbons to shallower and warmer waters. If microbial decomposition happened on the scale of the entire Deepwater Horizon blowout, then microbial breakdown may have produced a spectacular case of fairly rapid natural recovery from a stupendous human error, given the likely longer-term effects on shorebirds, perhaps future year classes of fish species, and the structural integrity of a number of marshes in Louisiana.

Do we have any evidence for such microbial action? Terry Hazen and a large group of colleagues (2010) investigated an undersea oil plume emanating from the area of the wellhead. This oil spill came at a time when next-generation sequencing methods allowed rapid molecular-based identification of bacterial groups specialized to degrade hydrocarbons. Reduced oxygen concentrations within the plume relative to outside of the plume indicated enhanced oil-degrading microbial activity. Confirmation of increased abundances of bacteria was found within the plume, especially genetic evidence for members of the Oceanospirales within the gamma-Proteobacteria, which are known to break down petroleum hydrocarbons. Molecular biologists could also use state-of-the-art methods of transcriptomics to study degrees of gene expression of the various bacterial groups associated with hydrocarbon degradation. High levels of gene expression of these bacteria was found for *n*-alkane and cycloalkane degradation, although activity for genes involved in breakdown of more resistant but abundant components (e.g., benzene, toluene, xylene) was low (Mason et al., 2012). Oil breakdown of some components was occurring faster than might be expected at the 5°C temperatures found near the bottom at the wellhead. Apparently, propane and ethane were the two main substrates used as energy sources by a very low diversity of bacterial species within the oil plumes (Valentine et al., 2010). Kessler and colleagues (2011) provided evidence that methanotrophic bacteria likely consumed all of the methane found in a large plume that stretched offshore of the Louisiana coast. Later, methane and aromatic hydrocarbons came to dominate the plume (Dubinsky et al., 2013). Hydrocarbons in crude oil were likely also broken down in large measure by bacterial groups (King et al., 2015).

The microbial community of Louisiana beaches also responded directly to the influx of oil, especially in the rapid expansion of bacterial species known to live on oils, as shown by a metagenomic analysis of beach sediment using 16S rRNA sequencing. Species capable of growing on oil as the sole carbon source also appeared. A transcriptomic analysis also demonstrated that expression of oil-degrading genes greatly expanded in beach microbial communities (Lamendella et al., 2014). Oil disappeared faster than in another oil spill studied in a colder and more pristine habitat. Again, the resilience of the Gulf seems notable.

HOT TOPICS IN MARINE BIOLOGY

Is the Gulf of Mexico Adapted to Oil? *continued* 22.1

Because studies were undertaken within restricted areas, we do not know what happened on the large scale of the Gulf of Mexico, but we can formulate a hypothesis: Long-term leaks of short-chain hydrocarbons in the Gulf have resulted in evolutionary change that increased the responsiveness of bacteria to hydrocarbons. It is well known that bacteria exposed to petroleum tend to be more capable of breaking down petroleum over time (Leahy and Colwell, 1990). This response could be merely the result of an increase in gene expression as exposure to oil induces certain genes, or it might be the result of natural selection, in which certain bacterial genotypes are selected over others by virtue of their ability to obtain energy and reproduce by breaking down oil more efficiently. As it turns out, there are very few seeps near the Deepwater Horizon site, so it may be the case that natural selection for oil-decomposing bacteria might have occurred throughout the Gulf. At any one place, rare occurrences of the oil-decomposing genotypes would be selected from low to high abundance when oil appears. It is important to realize that there is no strong evidence currently to prove that bacterial breakdown was responsible for the disappearance of any submarine oil plume. But there is every reason to believe that hydrocarbon-degrading bacteria were present both in deep waters and in coastal marshes before the oil spill. Warm water temperatures also probably accelerated degradation rates. Hydrocarbon-degrading bacteria likely increased in abundance as the oil spill hit, and a form of succession resulted in replacements of bacterial groups by others as specific hydrocarbons became uncommon (Valentine et al., 2012; King et al., 2015). The growth and expansion of hydrocarbon-degrading bacteria likely has had its own disruption on the microbial ecology of Gulf habitats, and it is of great interest to know when a new postspill equilibrium will be reached.

Despite the notoriety of major tanker and offshore drilling accidents, much oil is probably spilled during delivery of oil to harbor terminals. Spills occur when valves malfunction and when workers attempt to pump more oil into a tank than it can hold. U.S. law requires a set of containment booms to surround any marine loading area, but not all countries have legislation like this. Because of the lack of such a precaution, an August 1999 release from open valves of the tanker *Laura D'Amato* in Sydney Harbor, Australia, resulted in a spill of as much as 300,000 liters of Saudi Arabian crude oil along the shores there. The spill oiled thousands of shorebirds but dispersed from the shoreline after a few days. Chronic releases are important in increasing the concentrations of toxic substances, such as polycyclic aromatic hydrocarbons, in marine sediments (see later).

COMPONENTS AND EFFECTS OF OIL

■ The effect of oil varies with chemical composition and the affected organisms.

Oils may have the following components:

1. *Paraffins.* Straight- or branched-chain alkanes that are stable, saturated compounds having the formula $C_nH_{2n}12$.
2. *Naphthenes.* Cycloparaffins that are saturated but whose chain ends are joined to form a ring structure.
3. *Aromatics.* Unsaturated cyclic compounds that are based on the benzene ring, with resonating double bonds, and six fewer hydrogen atoms per ring than the corresponding naphthene. Often toxic, aromatics have been implicated in cancers.
4. *Olefins.* Alkenes, or unsaturated noncyclic compounds with two or fewer hydrogen atoms for each carbon atom. Olefins have straight or branched chains; they are not found in crude oil.
5. *Light gases.* Hydrocarbons of very short carbon chains (1–4).

The effect of oil varies with oil chemistry and the organisms affected. Crude oil usually has less than 5 percent aromatics and is widely regarded as the least toxic. Refined oil such as fuel oil may have 40–50 percent aromatic compounds. The toxic compounds in oil are known to impair cell membrane function and may impair behavior in a wide variety of organisms. As mentioned earlier, reproduction can be impaired in invertebrates exposed to these substances. Survival and development of fish eggs and larvae are also affected negatively. Phytoplankton production can also be reduced.

■ Oil affects seabirds via direct toxic effects and by disrupting the mechanical structure of feathers.

Oil has an especially devastating effect on seabirds. Birds maintain a high and constant body temperature, and **feathers** act partially as insulation. The fluffy **down feathers** provide an air space for insulation, and the air is sealed in by **contour feathers**. The **barbules** interlock efficiently, and the hydrophobic surface of the contour feathers helps to keep water from collapsing the downy layer beneath (**Figure 22.12**). Unfortunately, oil readily coats the surface of the contour feathers and collapses their interlock. Seabirds that come into contact with oil, therefore, soon lose their insulation and are likely to die of hypothermia. The oil also impedes flight, and the birds often ingest toxic oil while preening. (Some birds such as puffins are attracted to oil, as if they expect food to be found on the surface.) Both the *Torrey Canyon* and *Amoco Cadiz* spills caused the majority of the affected Atlantic puffins and other diving birds to cease breeding. These are some of the reasons oil spills are usually followed by conservationists' frantic cleanup efforts, but historically these efforts have been in vain (**Figure 22.13**). However, more recent efforts to remove oil from seabirds have been more successful. A study of cleaning efforts of penguins following a 1994 oil spill in South Africa estimated that about 75 percent of the cleaned birds

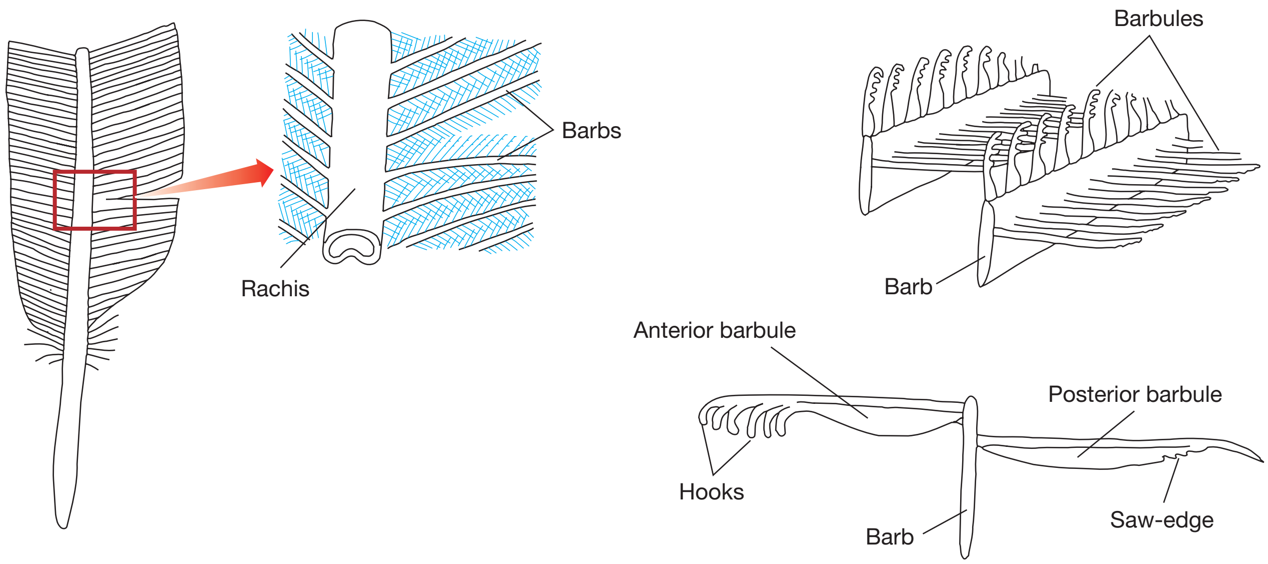


FIG. 22.12 The structure of a bird contour feather, showing the way in which the barbules are hooked together to seal the spaces between barbs. This interlocking system prevents water from penetrating to the downy layer of feathers beneath. (From Nelson-Smith, 1973)

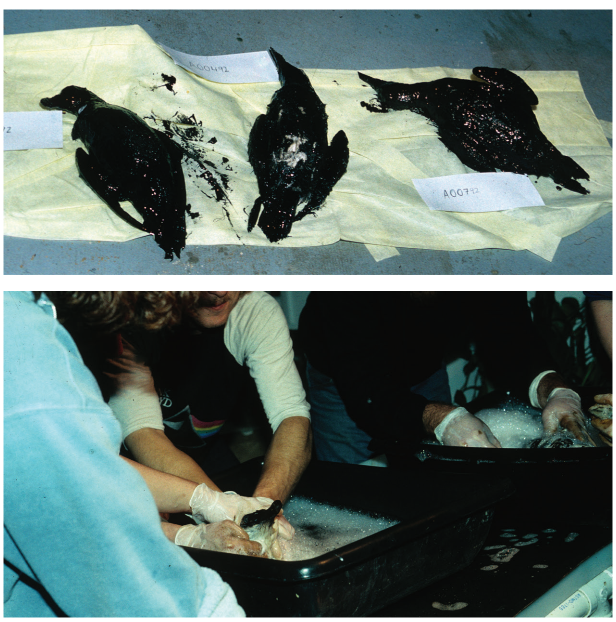


FIG. 22.13 (a) Birds washed but covered with oil from an oil spill. (b) Rescue workers attempting to wash oil from a seabird. (Courtesy of Sam Sadove)

successfully survived in the wild and that cleaning of birds significantly improved population recovery (Underhill et al., 1999). Considerable success was achieved in cleaning seabirds during the 2010 Deepwater Horizon accident.

OIL CONTAINMENT AND DISPERSAL

- **Oil spills can be contained with floats and are sometimes dispersed with emulsifiers or naturally by storms.**

Because of the devastating effects of oil, a variety of containment and dispersal methods have been developed. In active ports, oil spills may occur every day, and tankers now routinely have floating pens to contain any spilled oil. As mentioned earlier, chemical dispersants have been used extensively, but they often damage marine life further. Surfactants are usually lipophilic (oil-compatible) molecules with a hydrophilic (water-compatible) group at one end. This structure acts to emulsify—that is, to break up—oil. Although these materials are often toxic, they are used in moderation to break up oil slicks, thereby preventing seabird mortality. In some cases, wave action breaks up the oil, so even though it may harm the benthos, it does no damage to diving birds at the surface.

Oil tankers have become larger in the last few decades, and many so-called supertankers exceed 500,000 tons in capacity, moving approximately 2 billion tons of oil by sea each year. Although it is not possible to prevent all collisions, double-walled construction and individual oil compartments help reduce leakage. A series of international agreements has helped the process of compensation for nations victimized by tanker oil spills, but the strongly international nature of oil transport and the concept of freedom of the high seas make for difficulties in regulation and enforcement. The *Torrey Canyon*, for example, was registered in Liberia, owned by an American company, and under charter to a British concern. The wreck was technically in international waters, even though the oil affected both the British and French coasts. Such international complications prevent simple legal redress.

In many cases, the origin of oil spills cannot be isolated. Tankers often spill oil at sea, and minor spills from many small vessels combine to make large-scale oil pollution problems in ports. There has been considerable effort devoted to developing methods of analysis that might fingerprint oil, so that a community could identify the source of the spill. The most promising fingerprinting techniques involve chemical analysis of the hydrocarbons in oil. A technique known as gas chromatography–mass spectrometry is especially effective because it focuses on a number of compounds whose relative proportions can be used to pinpoint a particular oil with respect to its type and origin. Triterpenes and steranes are the most useful diagnostic compounds. Stable isotopes of carbon are also useful signatures of oil entry into marine food webs.

PAHs

■ **Polycyclic aromatic hydrocarbons (PAHs) are derivatives from fossil fuels. They are known to be carcinogenic in mammals and are major contaminants in coastal marine environments.**

PAHs derive from both point and nonpoint sources, including sewage systems, runoff, various oil spills, and burning of fossil fuels. They range greatly in molecular weight (there are mainly two-, three-, and four-ringed PAHs) and are adsorbed readily onto sedimentary particles, owing to their hydrophobic properties. PAHs therefore have become concentrated in coastal sediments and are widespread in near-shore bottoms in urban zones. PAHs can be toxic to benthic invertebrates, and various tissue abnormalities and cancers in fishes have been related to these compounds. Some PAHs can induce cancers in laboratory mammals, and their occurrence in resource species has troubled environmental managers. In the Hudson River, the tomcod *Microgadus tomcod* accumulates high concentrations of PAHs and other lipophilic contaminants and has high frequencies of liver tumors (Wirgin et al., 2006). Reduced performance has been related to a steady decline in reproductive success over the years. Bacteria in sediments degrade PAHs, but the rate of degradation is much slower for the higher-molecular-weight forms.

■ **PAHs and PCBs severely disrupt endocrine function in vertebrates and may be a major cause of reproductive failure.**

PAHs and PCBs both appear to strongly affect reproductive cycles, particularly in fishes. They act as **endocrine disrupters**, exerting their influence by mimicking the effect of endogenous hormones such as estrogens and androgens, antagonizing the effects of endogenous hormones, altering the pattern of synthesis and metabolism of normal hormones, and modifying hormonal receptor levels. In vertebrates, the secretion of gonadotropin-releasing hormone and follitropin from the hypothalamus and pituitary glands stimulates ovarian follicle growth and estradiol synthesis in the female. In oviparous vertebrates including fish, the release of estradiol from the ovary causes the liver to produce large amounts of vitellogenin, a lipoprotein precursor for egg yolk. Circulating vitellogenin and hormone levels in natural fish populations during the reproductive season have been shown to be a promising indicator of incipient reproductive dysfunction. High vitellogenin concentrations in male fish from contaminated environments have been interpreted as indicative of the estrogenic properties of contaminants.

Induction by PAHs and coplanar PCBs of *CYP1A*, the gene for cytochrome P450–1A, has been found to be one of the most sensitive if not the most sensitive response and has been used extensively in field investigations. The induction of the gene *CYP1A* is known to play a role in both detoxification and activation of toxic compounds and is also significant for health of the fish (Haasch et al., 1993).

Nutrient Input and Eutrophication

■ **Agricultural activities and sewage add nutrients, as well as disease organisms, to the water.**

Agricultural activities and sewage release cause a great deal of damage to marine life and contaminate fishes and shellfish. The major impact is the result of **nutrient release**, which indirectly reduces water quality. With sewage and animal waste, undesirable microorganisms are also released into the marine environment. Pathogens such as hepatitis viruses and the bacterium *Salmonella*, often concentrated by suspension feeders such as clams and mussels, may be the cause of a variety of diseases. Outbreaks of dysentery and other diseases can be common in areas where people collect shellfish near sewage outfalls and in heavily populated areas with septic tanks. Local environmental agencies in the past have counted the number of **coliform bacteria** in seawater, whose source must be the wastewater outlets. These bacteria are associated with the human gut and are counted because they are positively correlated with release of other pathogens. Fecal streptococci, or **enterococci**, have become a substitute indicator of pollution.

Nutrient Sources

■ **Human activities result in large additions of dissolved nutrients to coastal waters.**

Eutrophication is the addition of dissolved nutrients to a water body, resulting in large increases in phytoplankton production and microbial activity. In coastal waters, eutrophication is due to several nutrient sources related to human activity. The following are the principal known sources:

1. Point sources such as sewage treatment outfall pipes
2. Point sources such as storm sewer overflows (SSOs), which may be connected to sewage pipe systems
3. Nonpoint sources stemming from runoff from the watershed, with sources such as general runoff from agricultural and suburban lands owing to the use of commercial fertilizer, animal wastes, and increased supply of nutrients because of disturbed soils
4. Atmospheric deposition

Figure 22.14 shows an estimate of the relative contributions of nitrogen addition to the Chesapeake Bay watershed. Note that **agricultural sources** dominate, but there is a surprisingly large contribution from **atmospheric deposition**, which will be discussed shortly. Municipal wastewater is a considerable source, although septic systems are not. In areas such as New York Harbor and Boston Harbor, point sources such as **combined sewer–storm pipe outfalls and sewage treatment plant outfalls** are the major contributors

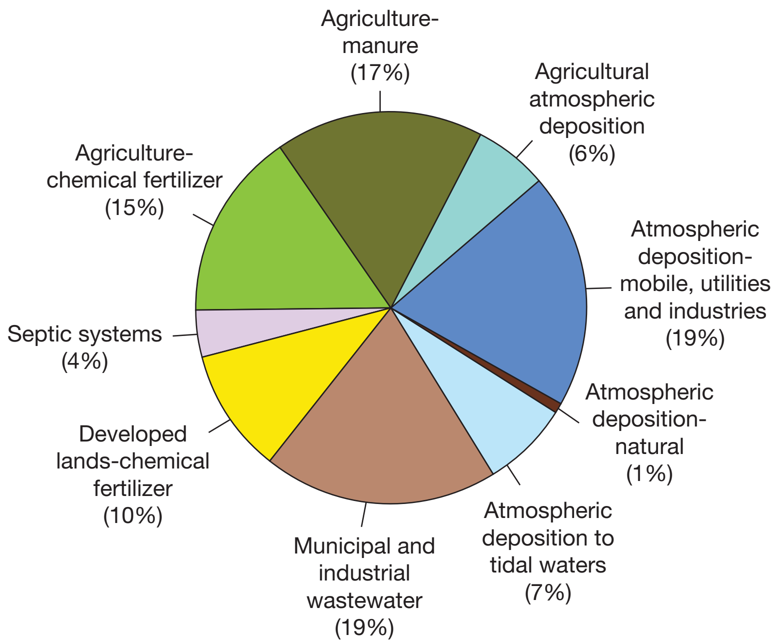


FIG. 22.14 Relative contributions of nitrogen to the Chesapeake Bay watershed. (Courtesy of the Chesapeake Bay Program)

of nitrogen. In New York Harbor, nutrient supply is so plentiful that nitrogen is often not a limiting factor to phytoplankton growth.

- **The atmosphere can be a major source of nutrient addition to coastal bays.**

Fossil fuel combustion is a major potential source of nitrogen oxide emissions. These gaseous emissions are eventually returned to the earth as soluble nitrates in wet or dry precipitation. The material becomes part of the now-famous acid rain, whose sulfur components may reduce the pH values of some lake and estuarine waters to the point of toxicity to fishes. The nitrates deposited by the rain are worrisome partially because they may stimulate primary production, which leads to eutrophication. Rainwater in the coastal zone can stimulate phytoplankton growth (Paerl et al., 2002). This effect is likely to be especially strong in more offshore shelf waters, where phytoplankton primary production is severely limited by nitrogen concentration. Along the east coast of the United States, atmospheric deposition accounts for 10–40 percent of the new nitrogen additions to coastal waters.

Effects of Added Nutrients

- **Nutrient stimulation of primary production often results in hypoxia or anoxia.**

Nutrient additions of nitrate and ammonia stimulate phytoplankton growth, as discussed in Chapter 11. At modest levels, one might expect higher water column and benthic production. These nutrient additions also stimulate bacterial production, however, especially in water columns where light is reduced. This is a problem in rivers and estuaries, where high particle loads reduce light penetration. As large populations of phytoplankton and bacteria build up, there is little likelihood that a zooplankton population will graze the phytoplankton. In the shallow waters of southern San Francisco Bay, the benthic suspension feeders can often keep up with the strongly eutrophic waters, and phytoplankton populations do not build up. This is not the case, however, in deeper estuaries with high nutrient loads and sluggish circulation. During the late spring and summer, when the water column stabilizes, much of the phytoplankton may die. Subsequent degradation by aerobic bacteria strongly reduces the level of dissolved oxygen, which is essential for nearly all animals (**Figure 22.15**). **Hypoxia** is the condition of strongly depleted dissolved oxygen. **Anoxia** is the complete absence of oxygen. Both hypoxia and anoxia may be accompanied by significant concentrations of hydrogen sulfide, which is toxic to many marine organisms. The lowered oxygen and the presence of hydrogen sulfide cause mass mortality of fishes and benthos. The rise of bacterial degradation is also exacerbated by the turbidity due to dense phytoplankton, whose shade prevents primary production in deeper water.

Nutrient addition to coastal waters has become one of the major world problems and has resulted in massive **dead zones**, near-surface bodies of waters nearly devoid of oxygen. Such zones have been found in the Black Sea, at the mouth of the Danube River, in the Baltic Sea, in the Gulf of Mexico near the mouth of the Mississippi, and in various sites in shallow seas of east Asia. In the typical case, large amounts of nutrients from a watershed are flushed out of a river into the coastal zone, stimulating primary production, microbial activity, hypoxia, and anoxia. An Oregon case was associated with the California current, usually a source of upwelling and never before associated with hypoxia on the Pacific continental shelf (Chan et al., 2008).

The dead zone off the mouth of the Mississippi (Rabalais et al., 2002) has been quite large: In 2007, it was approximately an area the size of New Jersey! Spring and

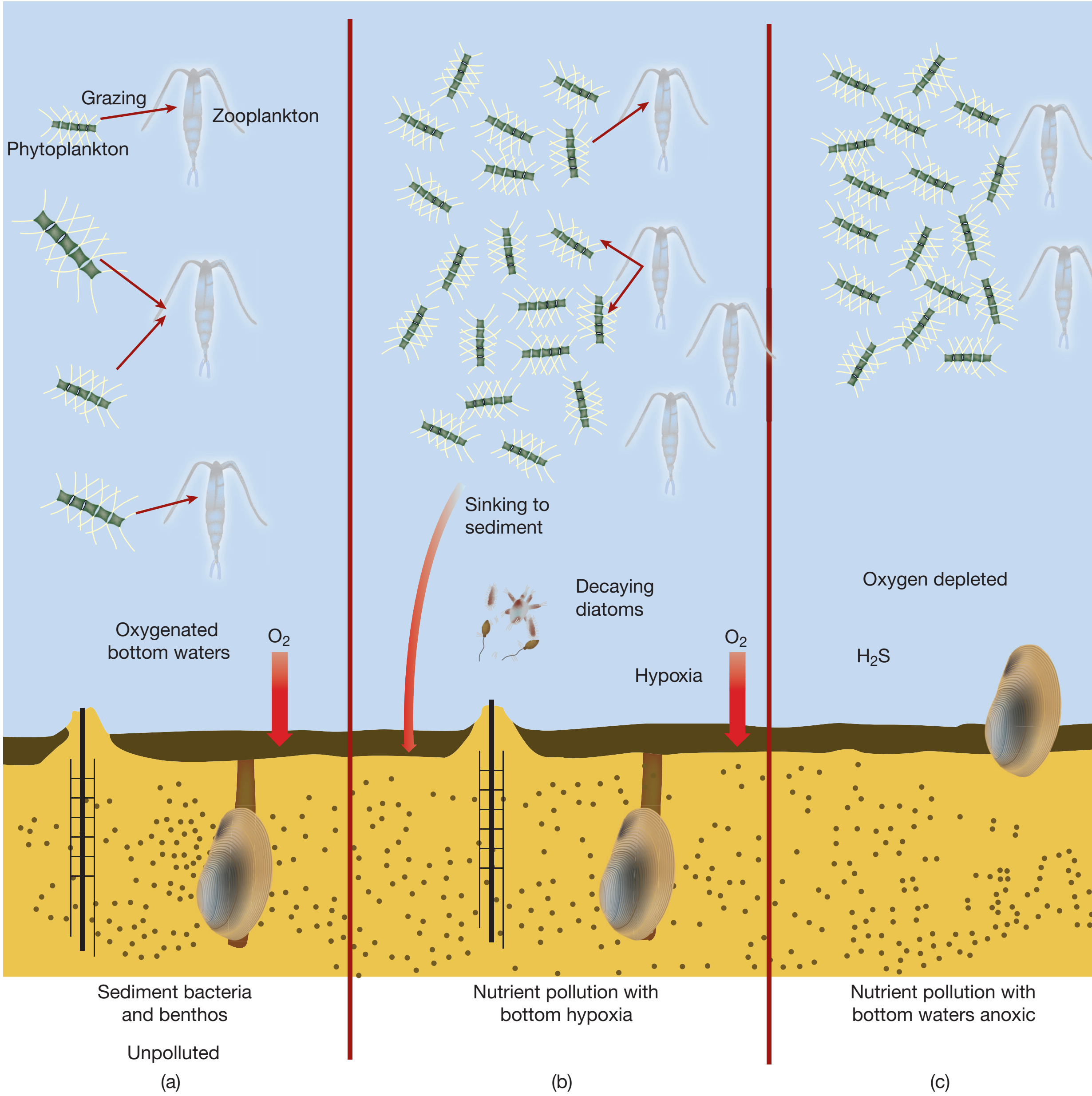


FIG. 22.15 Development of hypoxia in an estuary. (a) Normal situation: Much of the phytoplankton is grazed and bottom waters are oxygenated. (b) Nutrient input from sewage stimulates phytoplankton growth, and some dead phytoplankton sink to bottom waters; bacterial decomposition reduces oxygen, and other material sinks to bottom sediment, where more oxygen is consumed from bottom waters. (c) Oxygen is removed from bottom waters and benthos die.

summer conditions of surface water warming and high freshwater outflow create a strong density stratification, trapping nutrient-rich water in a stable water column near the coastal zone. The high microbial activity in this water body removes most of the oxygen (**Figure 22.16**). Studies from cores show that these conditions started around 1900 but became much more extreme beginning in the 1950s, when the Mississippi watershed was inundated with nitrates deriving from agricultural fertilization. The benthos beneath the dead zone consists of mainly small surface deposit-feeding annelids that respond to the deposition of particulate organic matter. The surface waters reduce fisheries, since fish either die or swim away from this stressful, poorly oxygenated water body.

ABATING EUTROPHICATION

- **Eliminating ocean dumping of solid sewage waste and better treatment of sewage before wastewaters are released into the coastal zone can abate eutrophication.**

Hypoxia and anoxia events in bays and estuaries have been frequent enough to draw public attention to the problem of nutrient additions, and sewage treatment has generally improved throughout the United States. Sewage treatment plants (**Figure 22.17**) typically practice **primary treatment,** in which solids are intercepted by screens, or **secondary treatment,** in which more toxic nitrogenous organic compounds and colloids are stirred in aerobic tanks so that only phosphates, nitrates, and ammonia will be released into

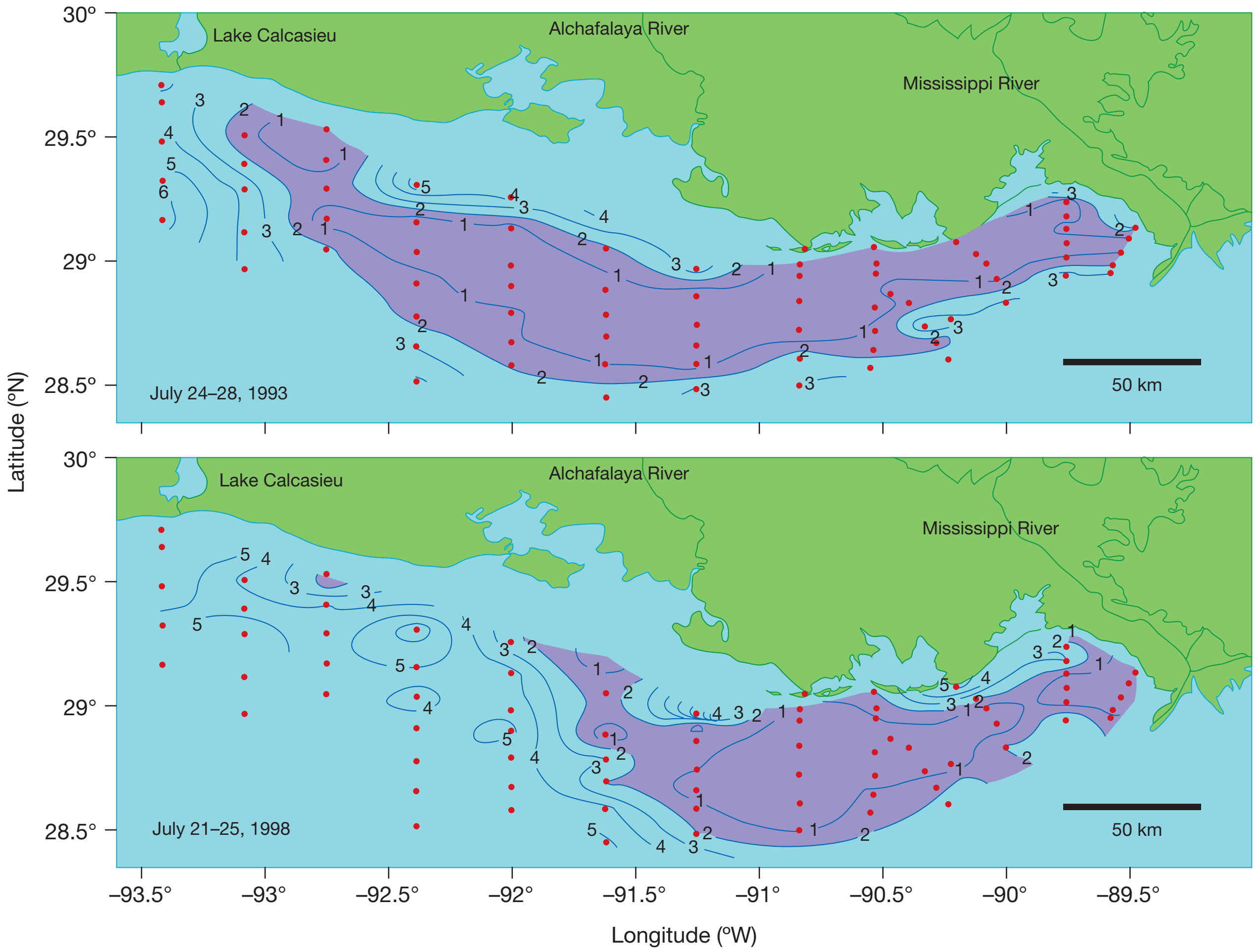


FIG. 22.16 Dead zone off the mouth of the Mississippi River. Bottom-water oxygen concentration contours in 1993 and 1998; shaded areas have concentrations below 2 mg/L. (After Rabalais et al., 2002)

coastal waters. The solid residue must then be disposed of. Very few treatment plants carry out **tertiary treatment**, in which even dissolved phosphates, nitrates, and ammonia are removed. Various anaerobic tanks may be employed to enable microbial removal of the dissolved nitrogen as gas, and iron is used to combine with phosphate; however, such practices are very expensive. These costly tertiary treatment methods, moreover, produce large amounts of sludge, which must be disposed of. Many municipal outfalls throughout the world do not even have primary treatment. The recent increases in hypoxia and anoxia events have stimulated interest in the expansion of secondary and tertiary treatments. Thanks to the improvement of sewage treatment, dissolved oxygen in New York Harbor has improved steadily over the last 50 years (**Figure 22.18**).

Recently, new methods of sewage treatment were introduced to provide a direct and workable alternative or addition to tertiary treatment. The ammonia reduction process (ARP) involves concentration of sewage sludge, removal of ammonia as gas by heating and pressure reduction, reaction with sulfuric acid, and conversion to ammonium sulfate, which can be used directly as fertilizer. This technology is being tested in New York City wastewater treatment plants and is predicted to reduce nitrogen inputs by about half. New York City has adopted a technique in Jamaica Bay in which ammonium is converted to nitrite and nitrate and nitrogen is extracted through the addition of glycerol as a carbon source.

The relative importance of nitrogen and phosphorus as nutrients becomes an important issue in tertiary treatment. Phosphorus is much cheaper to remove than nitrogen, although the ARP process or glycerol addition may prove economical. In most marine waters, nitrogen is generally believed to be the limiting nutrient. In estuaries, there is more room for dispute because phosphorus is known to be limiting in freshwater rivers. An extensive study of lower Chesapeake Bay shows that nitrogen is limiting there. This is a major problem because nitrogen does not come primarily from point sources, such as sewage treatment plants, but from a series of tributaries and general runoff. Control, therefore, will be very difficult.

- **Reduction of nutrient input into coastal bays and estuaries from point sources has been very successful in reducing phytoplankton in the water column, increasing water clarity, and allowing submerged attached vegetation to recover.**

Reduction of nutrient input in wastewater treatment plants, or point sources, has been a major objective in areas with

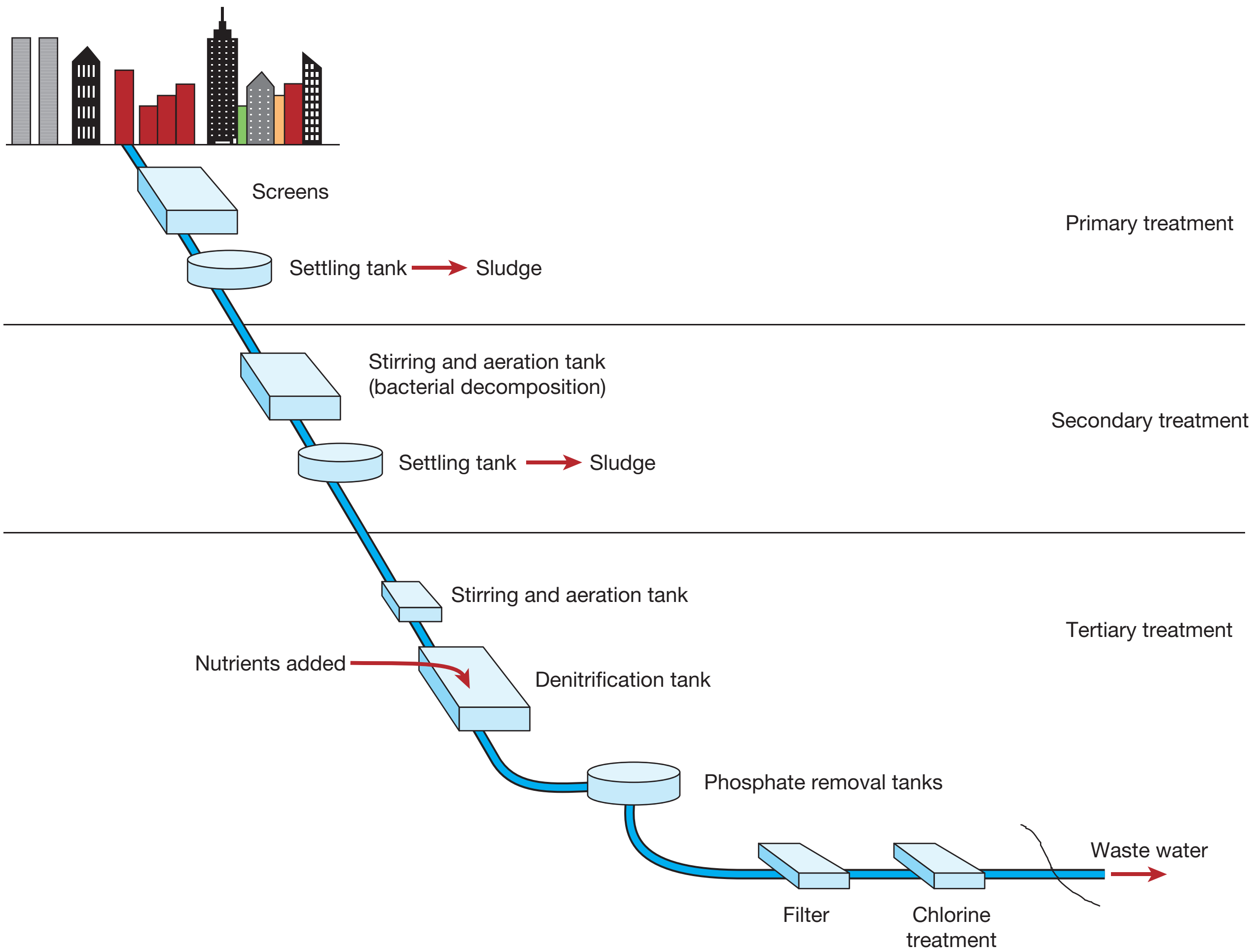


FIG. 22.17 Three types of sewage treatment.

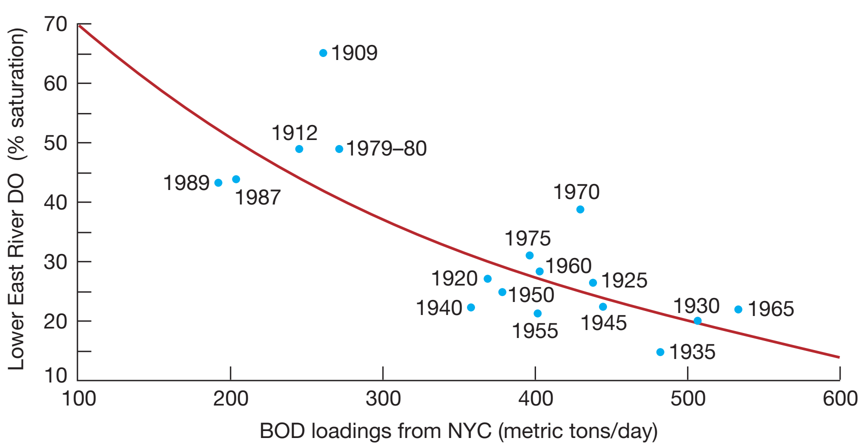


FIG. 22.18 The DO (dissolved oxygen) in the East River, New York Harbor–Estuary, as a function of the particulate organic matter entering the harbor from sewage (measured in terms of the potential biological oxygen demand [BOD] that the material places on the harbor waters). As BOD loading has declined, oxygen in harbor waters has increased. The years 1909 and 1912 probably represent times when material was released into marshlands and not directly through pipes into the harbor—hence, the lower BOD loading. (Courtesy of Dennis Suszkowski, Hudson River Foundation)

large urban and suburban populations. As discussed earlier, nutrients stimulate phytoplankton growth, which adds nutrients to the bottom sediments and causes hypoxia. Increased phytoplankton also intercepts light, which strongly affects and eventually eliminates sea grass growth, as discussed in Chapter 17. Nitrogen reduction is the target in saline waters, but phosphorus is also an important target in freshwater parts of estuaries.

In response to these problems, many coastal areas have instituted plans to reduce nutrient input, often with success.

An example is the Back River estuary near the city of Baltimore. Since the 1980s, a concerted reduction of nitrogen and phosphorus input has resulted in declines of nutrient concentrations and also of phytoplankton. This was especially noticed when wastewater treatment plants were upgraded in the 1990s. The positive response took a few years, probably because a large amount of nutrients remained in the sediment, which continued to fuel phytoplankton growth. Such reductions in phytoplankton also have resulted in increased water quality. Nutrients in Jamaica Bay were reduced from about 22,680 kg d^{-1} to 13,600 kg d^{-1} during the period 2010–2016. In Tampa Bay, a great increase of population growth resulted in heightened nutrient input and strong growths of phytoplankton and the green seaweed *Ulva*, which rotted on shorelines. At least half of the former sea grass beds had been lost because of increased turbidity caused by the phytoplankton. By 1981, upgrades of sewage treatment plants resulted in a 90 percent reduction of nitrogen input. Chlorophyll has been greatly reduced, and sea grass is recovering rapidly (Greening et al., 2011). Reductions of phytoplankton in the water column have also resulted in steady recovery of submerged attached vegetation in the waters of the Potomac River estuary (Ruhl and Rybicki, 2010). Overall in the Chesapeake Bay region, however, water quality has not improved, bottom communities have had reduced biomass diversity and abundance in recent years, and sea grasses are still in great decline. One thing the success stories have in common is that corrections could be made at the wastewater treatment plants because they are point sources of nutrients.

Thermal Pollution and Power Station Fish Mortality

■ **Power-generating stations require water for heating and as a result kill aquatic life, by entraining and impingement.**

Conventional and nuclear power stations require large amounts of water to transport heat from the power-generating system. Two popular means of heat dissipation are used. In the first, cold water is taken from a bay or river and passed through the plant; the heated water is then circulated through large cooling towers, such as those at the famous Three Mile Island nuclear facility in Pennsylvania. The towers then radiate heat into the overlying atmosphere. The relatively cool water is next returned to the river or can be recycled in a closed system between the power plant and the cooling tower. The second major approach involves removing water from a bay or estuary, passing it through the plant, and returning it quite hot to the environment. Typically, the water is returned to a man-made embayment and then passes out to the adjacent estuary or coastline while still approximately 10–15°C over ambient temperature. The released warm-water effluent may also form a plume that moves out into the open water. A warm-water plume may attract fish that should instead migrate away from the otherwise cooling waters in the autumn. If the plume should dissipate during a storm, the fishes probably would die owing to the cold shock.

Whether or not the returned water is heated, the uptake of large volumes of water at intakes creates the problems of **entrainment** and **impingement** of fishes. Eggs, larvae, and juveniles may be entrained or moved through the intake pipe, passed through the power plant system, heated suddenly, and returned to the open water through an outflow pipe. A significant amount of mortality is often associated with this passage. If the fishes are larger, they may be impinged, or trapped, on the intake screens, which often kills them.

Impingement results from the strong pressure created by water intake pumps. Various screens have been designed, partially to reduce fish kills but mainly to keep pipes from clogging. A barrier net placed in the surrounding area can be helpful, but such nets often become fouled with algae and sometimes cannot be deployed in summer. At intake sites, the angle screen is a popular design because it may divert fish along itself to an exit pipe, supposedly reducing fish mortality, but this has been questioned (Fletcher, 1985).

■ **Thermal emissions may also affect plant production.**

Thermal pollution may inhibit phytoplankton growth and change the character of plant communities in the vicinity of warm-water outfalls. In the Turkey Point nuclear generating station outfall in South Florida, turtle grass was replaced by blue-green cyanobacteria. The hot waters were often too extreme for all but the hardy blue-greens. Similar effects have been observed throughout the world—for example, at Zhanjiang Bay China, where thermal effects reduce phytoplankton production and diversity (Li et al., 2014). Usually, thermal effluents are a certain number of degrees above ambient and therefore exert their strongest effects when summer water temperatures are maximal. These effects, however, are strongly localized, especially when the outfall mixes with coastal waters of high current energy.

Global Environmental Change and the Ocean

Throughout the text we have described the main effects that exist and may continue to develop as a result of global climate change. Here we will summarize these effects and briefly outline their collective possible future impact on marine biological processes, from the level of individual function to the level of biodiversity.

The Effects of Burning of Fossil Fuels and Additions of Greenhouse Gases

■ **Industrial activities have caused the net addition of carbon dioxide and other greenhouse gases to the atmosphere since the nineteenth century. These additions are significant on a geological scale.**

Human activities have reached a point at which they are altering the earth's global climate. Since the Industrial Revolution in the nineteenth century, industrial activity has greatly accelerated the burning of fuels, particularly fossil fuels, such as coal and petroleum products. Mainly as a result of this activity, approximately 35 percent has been added to the storehouse of carbon dioxide in the earth's atmosphere. Measurements from Mauna Loa, Hawaii, and other inferences suggest an increase from 280 ppm in the nineteenth century to the current concentration over 400 ppm. Deforestation and other greenhouse gases are secondary sources of carbon release or heat storage.

- **Carbon dioxide additions to the atmosphere have caused increases of sea-surface temperature through at least the past 150 years.**

In the past 150 years, ocean temperature has increased throughout the world, with rather large changes in the Arctic Ocean and in the Antarctic Ocean near the Antarctic Peninsula. Widespread increases have also been recorded in coastal areas of New Zealand, British Columbia, and Massachusetts, and within the Hudson River and Chesapeake Bay. Records at Woods Hole and the Baltic Sea date back to the nineteenth century, and one can see an acceleration of temperature rise in the past 35 years. Worldwide (excluding the Antarctic Ocean), sea-surface temperature has increased approximately 0.6°C from about 1900 to 1990 (Rayner et al., 2003). Sea ice has also been affected, most intensively in the Arctic Ocean, the Barents Sea, and the Antarctic Peninsula.

- **Carbon dioxide additions have resulted in a reduction of seawater pH.**

As explained in Chapter 3, carbon dioxide additions to the atmosphere eventually increase dissolved CO_2, which increases ocean acidity. Ocean pH has declined in the surface ocean, although data are only sparsely available. A decline of 0.1 pH unit has been measured ocean-wide, but higher rates have been noticed, for example, in the northeastern Pacific. Within estuaries, pH fluctuates a great deal and low values are to be expected even now, especially when oxygen is depleted, causing microbial activity and increases of dissolved CO_2.

BIOLOGICAL EFFECTS AT THE INDIVIDUAL LEVEL

- **Increases of sea-surface temperature affect physiological function, migration patterns, and geographic range.**

Increased sea-surface temperature exerts a variety of physiological functions. Increased temperature will affect cellular oxygen demand, which may be limiting. Species at the low-latitude end of their current geographic range will have their ranges curtailed, as has occurred for the common mussel *Mytilus edulis* on the east coast of the United States. In some cases, this will involve species trapped within estuaries, which will cause local extinction. Increases of ocean temperature at the low-latitude end of a geographic range may also affect migration patterns and foreclose some feeding and spawning areas to some species. At the high-latitude end of a species range, different species may move to cooler waters. For example, in the North Atlantic, some essential plankton species have moved northward, which has starved sand eels, whose decline has caused reproduction crashes in a number of nesting seabirds in Scotland (Dybas, 2006).

Ocean warming has already exerted some significant changes in reproductive cycles and marine migration patterns. In the North Sea, echinoderm reproductive cycles have been advancing in time over the past few decades, as sea temperature increases (Edwards et al., 2009). Climate change in the northeastern Pacific has caused increases of sea temperatures, and recent work in a warming Alaskan stream demonstrated that migration patterns of pink salmon populations have evolved in the past 4 decades to shift their return to rivers earlier by 2 weeks (Kovach et al., 2012).

Some species or groups will suffer quite specific effects. We discussed coral bleaching in Chapter 18 and the effect of increased temperature, which is well known from studies of effects of ENSO events. A number of predictions suggest widespread increases in bleaching in coming decades. Temperatures in the Caribbean can now be predictably related to coral bleaching. As discussed in Chapter 17, a number of large-scale bleaching events have occurred in recent years, and the northern third of the Great Barrier Reef witnessed unprecedented bleaching in 2016.

- **Increases of sea-surface temperature may affect the impact of disease spread.**

The spread and effects of disease may be strongly affected by increases of ocean temperature. Species that are physiologically stressed by high temperature may be more susceptible to disease. Some infectious diseases may spread to higher latitudes as temperatures increase. Disease in oysters and other bivalves has increased in the northeastern United States, and this may continue with regional warming. The oyster disease Dermo is moving northward in the eastern United States as warming occurs.

- **Decreases of pH are influencing calcification.**

In certain parts of the ocean, such as the northern Pacific, there already is evidence that increases of ocean acidity will soon affect calcification in organisms ranging from calcareous plankton to corals. Recent evidence suggests that bivalve larval shells are already being affected, relative to presumed levels of atmospheric carbon dioxide in the nineteenth century. Larvae of the bivalve *Mercenaria mercenaria* showed improved survival, growth, and metamorphosis when grown at preindustrial levels of carbon dioxide, relative to those of the present day (Talmage and Gobler, 2010). Species that secrete the less stable form of calcium carbonate, aragonite, are at greater risk than species with skeletons composed of calcite. Because the solubility of calcium carbonate increases with ocean depth, some deep-sea species, such as the corals that live on deep-sea coral mounds, are at risk in depths of 800–1,000 m. As we discussed in Chapter 17, reduced calcification of corals on the Great Barrier Reef in recent years may be related to acidification. Increased CO_2 may increase primary productivity, as it has done in terrestrial experiments; but in the long run, lowered pH will also affect calcifying plankton.

BIOLOGICAL EFFECTS ON BIODIVERSITY

■ **Changes of pH and sea-surface temperature may cause the loss of foundation species for major communities.**

Temperature and associated changes have particularly strong impacts when they affect foundation species in communities. We have discussed a number of communities where dominant living species function as foundation species. Kelps are adapted to cool oceanic waters, and global sea-surface temperature change will likely have strong effects on a number of kelp communities. These impacts are to be expected in both the North Pacific and North Atlantic, and *Laminaria* stands in southern New England are likely now at risk. Temperature-induced bleaching will cause extensive coral mortality, and thousands of species depend on dominant corals in tropical coral reefs. Minimally, there will be strong rearrangements in dominance. Such problems may interact with another predicted associate of global warming, intense storms. Such storms were already instrumental in destroying the typical coral-dominated communities on the north coast of Jamaica, as discussed in Chapter 17.

■ **Changes of sea-surface temperature may cause increases of the success of invasions of alien species and rearrangements of local species abundance.**

Increases of local sea-surface temperature may have a dual impact. On the one hand, native species might suddenly be subjected to temperature stress. But invasive species from warmer water sources might be able to invade and outcompete local species, which were adapted to cooler temperatures. This process appears to be important in the invasion of Long Island Sound, New York, by warmer-water colonial sea squirts. Because local disturbance is an important source of increased risk of invasive success, we can expect global warming to result in increased success of invasive species. We also expect that invasive species will be predominantly warm-adapted or thermally tolerant. The worldwide invasive crab *Carcinus maenas* is notable for its wide thermal tolerance (Tepolt and Somero, 2014), which has allowed it to invade warm and cold waters alike.

■ **Overharvesting of species or habitat destruction may result in complex negative interactions with global climate change impacts.**

The marine realm has been very disturbed by human activities, ranging from habitat destruction to strong overfishing. As temperature increases in some localities, it may become very difficult to restore communities that have been removed by human activities.

■ **Increased temperature may cause sea-level rise and major changes in oceanic circulation.**

Sea-level rise will be caused by a combination of ocean warming, increasing water volume, and melting of glacial ice. Drowning and rearrangement of estuarine circulation patterns, erosion of marshes, and changes of erosional regimes of sandy shores and barrier bars are all likely outcomes. Storm surges will make some of these effects catastrophic, as in the recent impacts of Hurricane Sandy on the northeast United States. On a more subtle level, melting of Arctic Ocean sea ice has resulted in major changes of productivity patterns and plankton patterns in the northwest North Atlantic continental shelf plankton communities (see Chapter 19 discussion on Arctic climate change).

■ **Sea-level rise and climate change may strongly affect coral reef survival.**

Grigg and Epp (1989) suggested that sea-level rise owing to global warming might outstrip coral growth, which would trigger a worldwide catastrophe. More locally, some reefs are located on sinking oceanic islands and might be vulnerable. Drowned coral reefs have been found throughout the Pacific, but it is not known whether drowning occurred under circumstances similar to today's conditions. Even if the reef were able to grow as sea level rose, increasing sea temperatures might cause extensive coral bleaching and contraction of reef systems. El Niño periods often exceed the thermal limits of hermatypic corals, and general warming could lead to catastrophe. It is not clear, however, that the thermal effects would overwhelm all reef species; some might survive better than others, perhaps coming to dominate a new reef community able to survive warmer temperatures.

■ **Increased temperature and carbon dioxide may increase biological productivity, especially in nutrient-enriched estuaries.**

Any prediction of how global warming might affect production in the ocean must be extremely speculative. Carbon dioxide increases can stimulate plant growth, which may increase primary production in waters in which nitrogen (for example) is not strongly limiting. One can imagine a scenario in which currents increase and bring deep-water nitrogen to the surface while increased carbon dioxide increases photosynthesis. In some polluted estuaries (e.g., New York Harbor), nutrients are not limiting during the year, and primary production increases as a response to increasing temperature. Under such circumstances, global warming might increase primary production, which in turn would cause more waters to be hypoxic, as explained earlier in this chapter. The appearance of dead zones throughout the world in recent years may be related to climate change. As discussed in Chapter 11, some common phytoplankton such as coccolithophores are known to respond positively to carbon dioxide additions to seawater.

■ **Increase of greenhouse gases and global warming could intensify coastal upwelling and increase primary production.**

Any process affected by temperature change may be affected by global warming. One of the most likely factors to be affected is the balance of winds along the coastline. As discussed in Chapter 11, upwelling and enhanced primary productivity occur in regions where wind stress brings nutrient-rich deep water to the surface. Along the California coastline, northerly and northwesterly winds cause the offshore transport of surface water, a process that is in turn balanced by a rise of nutrient-rich deep waters. Global warming can accelerate such a process because daytime temperature on the adjacent land will increase and nighttime cooling will decrease. This overall temperature increase will accentuate the temperature difference between the land and the adjacent cool ocean, which will intensify winds and upwelling. Andrew Bakun (1990) has demonstrated that wind speeds in upwelling regions have steadily increased since the 1950s, when data first began to be collected, and this finding is consistent with the steady increase in greenhouse gases. An increase in primary productivity has not been measured but likely has occurred because upwelling of nutrient-rich deep water is the limiting factor in these systems. Whether the changes have, or will have, an enhancing effect on fisheries is not yet clear.

■ **Changes in primary production may occur in the open ocean over a few decades, but there is mixed evidence at present that primary production has increased to any degree over the last 70 years or so.**

As discussed in Chapter 11, we might expect sea-surface warming to produce increased stratification, reduced vertical water exchange, and reduced primary production in surface waters of the open sea such as gyre centers. The evidence of change on the scale of 50–100 years is mixed, but reduced primary production in the open ocean near gyre centers since the 1980s has been confirmed.

CHAPTER SUMMARY

- Pollution has both chronic (long-term) and acute (short-term) sources that impact the marine environment. Complex interactions among human impacts from many sources can make it difficult to pinpoint the role of particular pollutants.
- Common species are often chosen as bioassays of pollution and its effects on mortality, population growth, physiological condition, and gene expression. Studies may correlate the release of toxic substances with their uptake by individuals. Some populations evolve resistance to toxic substances.
- Many toxic substances transfer from one trophic level to the next as predators consume prey. In the process, the concentration of some substances is biomagnified, reducing biodiversity at the highest trophic levels.
- Heavy metals, including lead, cadmium, and mercury—as well as the deadlier *methylmercury*—are toxic to humans. Pesticides and polychlorinated biphenyls (PCBs) washed into coastal waters are often toxic to marine life. Other major contaminants include oil, particularly refined forms, and derivatives of fossil fuels called polycyclic aromatic hydrocarbons (PAHs). They are known to be carcinogenic in mammals and are major contaminants in coastal marine environments. PAHs and PCBs disrupt endocrine function in vertebrates and may be a major cause of reproductive failure.
- Human activity adds greatly to dissolved nutrients in coastal waters. Sources include sewage, nonpoint coastal sources, and atmospheric deposition. Nutrient stimulation of primary production often results in hypoxia or anoxia. Most worrisome are coastal dead zones. Eliminating ocean dumping and having better sewage treatment before wastewaters are released can abate eutrophication.
- Industrial activities have been adding greenhouse gases to the atmosphere since the nineteenth century. As a result, increasing sea-surface temperatures have likely increased the spread of disease and affected physiological function, migration patterns, and geographic range. The declining pH of seawater has caused the danger of reduced calcification. These changes may bring about the loss of foundation species for major communities. Sea-level rise and climate change may also directly affect coral reefs, mangroves, and salt marshes.

REVIEW QUESTIONS

1. What are the differences between point sources and nonpoint sources of pollution?
2. What are three general approaches that can be used to assess the overall effects of pollution in a given habitat?
3. Why are pesticides, which are designed to kill terrestrial arthropods, often quite dangerous in marine ecosystems?
4. Why is mercury a particular danger?
5. What effects does spilled oil have on marine environments?
6. Why does oil composition and type matter with regard to toxic effects?
7. Why has the treatment of oil spills sometimes been as damaging as the oil spills themselves?
8. Nutrient input increases primary production, which should support more fish. So why are people upset about increasing sewage input throughout the coastal ocean?
9. How does nutrient enrichment lead to hypoxia?
10. In what type of marine environment is atmospheric deposition of nutrients likely to have the greatest effects?
11. Why are plants that generate electric power a potential danger to fish stocks?
12. Which marine environments do you think are more vulnerable to pollution: tropical ones or those in high latitudes? Why?
13. Why has carbon dioxide increased greatly in the atmosphere in the last 100 years or so?
14. How might carbon dioxide increase affect global climate? Oceanic circulation?
15. Why would it be useful to use microarray approaches to studying responses to pollutants?
16. If a toxic substance is removed from an area, what might happen to a

species population that had evolved resistance to that particular pollutant?

17. Why do you think that exposure to two different toxic substances might have very strong effects on an organism, much more than the sum of the individual effects of the two substances?
18. We have shown that in many cases populations can evolve resistance to pollutants. Does that mean that pollution is not really a problem in the marine environment? Under what circumstances to you think that evolution to pollutants might not occur?

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