CHAPTER SEVEN

Plankton and Pollution

> Those who will not understand science, become instead its prisoners.
> Charles A. Lowe

The final step in studying plankton is to understand how plankton and people interact. Civilization faces a great dilemma with respect to the sea: while being subjected to an uncontrolled experiment on the effects of waste disposal, the oceans are also looked to as a food source for unborn millions. We demand more of the ocean's biological wealth, while we burden it with more of our refuse. Both plankton and Puget Sound are at the center of this paradox, because both are battlegrounds for the conflicting demands of food supply and waste disposal.

Plankton plays a pivotal role in the responses of the ocean to pollution. Plankton is itself directly affected by pollution, but it can also act as either a conduit to or a shield for higher animals. The plankton is a gateway between the sea and the land, by which food is transported to people, and through which waste travels in return.

Puget Sound is a microcosm of these relationships. Here, in one place, is both a bountiful food supply with great potential for expansion, and a convenient dumping ground for the waste of human populations and industry. Today parts of Puget Sound are as pristine as forested wilderness, and parts are as developed and degraded as urban sprawl. There is no simple reconciliation of the needs for both more development and less impact. The best hope lies in combining an objective, scientific attitude with a spiritual appreciation of our relationship with the sea.

Human impacts on the sea have received intense publicity in recent years, and have aroused public indignation due to a number of catastrophes. Examples come easily to mind. Oil spills like the *Torrey Canyon* in 1967 off England and the *Amoco Cadiz* off France in 1978 blackened miles of shoreline and wounded local economies. Consumption of mercury-tainted seafood at Minamata, Japan, produced a wave of human death, illness, and birth defects through the 1950s and 1960s. Many species of marine mammals—whales, fur seals, and sea lions—in the Pacific Ocean and worldwide have been slaughtered to near extinction. The temporary decline in populations of seabirds off southern California led, as much as any other factor, to the banning of DDT for most uses in the United States. Attitudes toward exploitation of the sea have changed dramatically in the last two decades, along with attitudes toward resource use and pollution in general. Americans have reached a point where no actions can be taken, on sea or on land, without careful scrutiny of their possible effects on the environment.

But tracking down sources of pollution, determining the nature and extent of their effects, and prescribing cures can be complex tasks. A pollutant may be chemical or thermal; it may originate from as specific a source as a factory, or as diffuse a source as ocean-going vessels. Tons of one pollutant might be safer than teaspoonfuls of another. Some apparently serious threats are not so serious, and some of the worst menaces may be unpublicized and virtually invisible. The effects of a pollutant may appear far from its source, in some subtle ecological disguise. Each pollutant behaves in a unique fashion, and must be evaluated individually.

Science, therefore, has established a protocol—a common, agreed-upon set of rules by which all the pollutants may be judged, and their hazards determined. It involves gathering as much information as practicable about certain aspects of pollutants before passing judgment. The rules of the protocol are as follows:

Know the background level of the pollutant. Practically any substance, even water, is harmful to marine organisms in excessive quantities. Conversely, however, apparently any pollutant can be tolerated in a small enough dose. Certain pollutants are entirely natural or even essential substances, such as nutrients and minerals, which human activities have concentrated to an abnormal degree. These have consequences very different from those of anthropogenic substances, which owe their very existence to civilization. The hazard posed by addition of a substance to the sea depends on the amount already present, and on the degree to which human activities would alter that amount.

The concentrations of pollutants in water are commonly measured by the fraction of weight they contribute when mixed with water, in the same fashion as the salinity. Salt is present in Puget Sound seawater at concentrations of two to three percent by weight, or 20 to 30 parts salt per thousand parts water. Nutrients such as inorganic nitrogen are usually present at the surface of the Sound at 100 or more parts per billion, or 100 micrograms in a kilogram (one liter) of water. The ranges of concentrations of pollutants that are harmful to marine organisms can vary all the way from the parts per hundred (tens of grams per liter) down to the low parts per trillion (billionths of a gram, or nanograms, per liter). It does not take much of a compound to make up such low concentrations. At its present concentration of PCBs of roughly two parts per trillion, for instance, the approximately 2×10^{14} (200 trillion) liters of water in Puget Sound contain only about 400 kilograms (880 pounds) of material.

Know the sources and sinks, and their rates. A sink is the opposite of a source; it is a pathway of removal, a final resting place. No constituent of seawater is static; all are constantly being added and subtracted by various mechanisms. The relatively constant salinity of the sea, for example, is sustained by a dynamic balance of minerals constantly washing from land and settling to the sediments, and of fresh water cycling between land, air, and sea. Any accounting of human alterations must consider many natural and potential rates of supply and removal, as well as existing background levels.

Know the pathways between source and sink. Most pollutants in the sea ultimately end up on the bottom, but they might reach their destination by many routes. When determining the biological effects of such substances, the intermediate fates between source and sink must be traced, lest some important impact be overlooked, or the relative importance of various pathways be misunderstood.

Know the biological interactions. The effects of pollutants on living things are as individual and varied as the chemicals and organisms involved, and it often takes years of research to pinpoint the who, where, why, and how of their impacts. Nevertheless, some generalizations can be made. It is important, first of all, to distinguish whether a pollutant reaches an animal through direct uptake from the water, or through trophic uptake from its food. The latter is potentially far more serious, since it is the mechanism by which biomagnification, the progressive elevation of pollutant concentrations in the tissues of animals at successively higher trophic levels, takes place. Secondly, we must distinguish between acute and chronic, or lethal and sublethal effects. The immediate and obvious effects of toxins (including death) are dangerous; but because they may be delayed, or are too subtle to notice, long-term effects of small quantities of pollutants may be even more sinister. In addition, the effect of one pollutant may be modified by the presence of others. This synergism between pollutants—for example, the heightened sensitivity of an animal to one pollutant when it is already fighting the effects of another—can occur in numerous combinations. On the positive side, however, individual animals can acquire a tolerance to low levels of pollutants after a period of exposure. Furthermore, many plants and animals have the ability to depurate pollutants—that is, to eliminate them from their systems once placed in clean water—or to metabolize them and break them down into harmless by-products.

There are three classes of interactions between plankton and pollution. First, pollutants of various kinds have direct effects—usually toxic but sometimes stimulatory—on planktonic plants and animals. Second, plankters in return influence the physical and chemical conditions of pollutants in seawater, and can significantly affect their ultimate fate. Finally, of perhaps greatest interest is the possible role of plankton in the biomagnification of pollutants and in pollution effects both on the Puget Sound food web and on humans.

Effects of Pollution on Plankton

The first step in tracing the fates and effects of pollutants is to examine their direct impacts on plankton. Figure 7.1 presents the concentration ranges of some pollutants in Puget Sound, compared to minimum values found to harm plankton. Toxicity varies widely, depending on the pollutant, and the values displayed can be misleading if not properly interpreted. Most of the concentrations of dissolved pollutants in Puget Sound are at the low ends of the ranges presented, with just a few polluted sites (e.g., lead at a dredge spoil site in Elliott Bay, mercury in Bellingham Bay, arsenic off Tacoma) providing the

Pollutant Toxicity and Concentrations

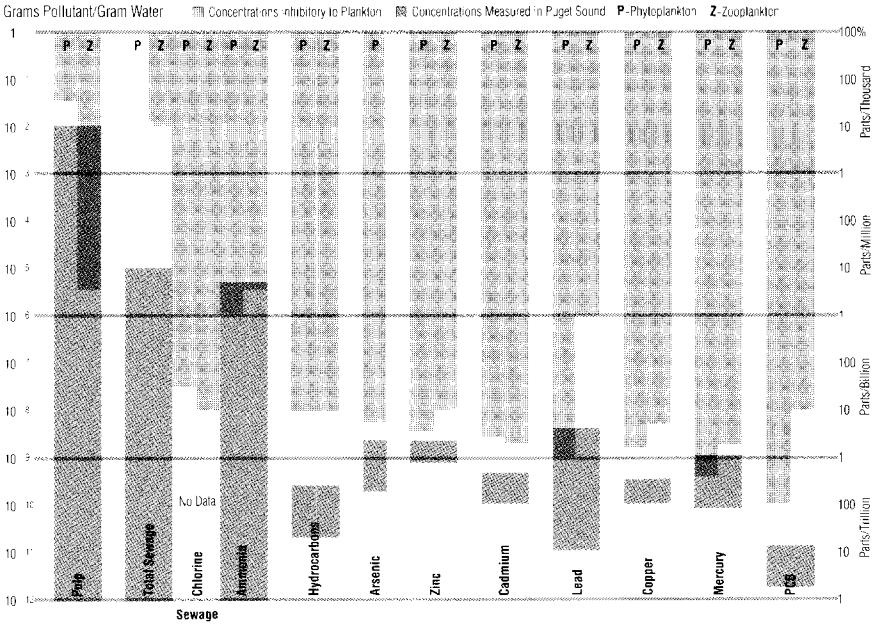

Figure 7.1 Measured concentration ranges of several pollutants dissolved in Puget Sound waters, compared to concentration ranges shown to be hazardous to plankton. Concentrations are displayed as a fraction of water mass on a logarithmic scale. Overlap of the two ranges for a given pollutant indicates potential damage to plankton. Concentrations of dissolved pollutants in most regions of Puget Sound are near background levels, with just a few polluted sites (e.g., lead at a dredge spoil site, mercury in Bellingham Bay, arsenic in Commencement Bay) providing the high values. Some of these measurements were made before recent cleanup efforts. Likewise, the concentration thresholds at which plankton is harmed are set by a few sensitive species, and most plankters are hardier.

high values. Many of the minimum unhealthy values of pollutant concentrations are for particularly sensitive species; the same values may not affect or may even stimulate other species. Furthermore, the logarithmic concentration scale shows increments of tenfold, making differences appear smaller than they would on a normal arithmetic scale. In general, the wider the range in concentration of a pollutant in the Sound, the greater the human input; this is particularly evident for such pollutants as lead.

Figure 7.1 shows that pollutant levels in Puget Sound waters are mostly below toxic thresholds. There are few documented cases of pollutant injury to plankton here, and recent research suggests that toxicity is more closely related to pollutant burden within the plankton itself than to that of the waters. The major categories of pollutants are discussed individually below, roughly in order of increasing toxicity to plankton.

Sewage

Least toxic of the pollutants—in fact, stimulatory under most conditions—is sewage. Until the 1960s, much of the waste of the Seattle metropolitan area went into Lake Washington, with results similar to those in many other bodies of fresh water that received the same abuse. The lake became eutrophic: cloudier, greener, fouled by algae, and filling in prematurely. The lake was overfertilized by the nutrients in detergents and human waste, especially phosphorus. Since the 1960s, Lake Washington has begun to return to its original state, because the sewage has instead been diverted into Puget Sound. The obvious question then is, can the same thing happen to Puget Sound that happened to Lake Washington?

Municipal sewage, before being discharged into the Sound, currently receives what is called primary treatment: the waste water is screened, held in ponds to allow much of the solid sludge to settle out, and disinfected with a spurt of chlorine. Federal regulations require sewage to undergo secondary treatment, in which the effluent is further retained and filtered to allow bacteria to digest sludge. This process can remove 95 percent of the solid matter in the effluent, although 90 percent is a more customary figure for discharge to salt water. The effluent that enters salt water from either treatment process is rich in both organic and inorganic forms of two elements, nitrogen and phosphorus, which promote the growth of phytoplankton. Tertiary treatment, used on effluent discharged to fresh water, involves removal of these nutrients as well.

Before its effects can be known, it must be determined whether sewage effluent significantly alters the chemical composition of the Sound's waters. In the case of much of Seattle's sewage, the answer appears to be no. Most bodies of salt water are more sensitive to changes in nitrogen supply than to that of phosphorus. They are also better flushed, and so effluent is better dispersed than in most lakes. Puget Sound already has an abundant background level of nutrients, which in the main basin is seldom low enough to limit phytoplankton growth. Vigorous currents and vertical mixing serve both to replenish surface nutrient supplies and to disperse and dilute sewage effluent. The natural flushing of nutrients in and out of this portion of the Sound far exceeds the amount added by people. Effluent from the city's West Point treatment plant is released near the bottom, at a depth of about 70 meters, where nutrients are abundant and the effluent is unlikely to affect plankton. Likewise, waste from the Renton treatment plant (which already receives secondary treatment) appears not to affect the frequency of phytoplankton blooms near the mouth of the Duwamish River, into which it is discharged.

In contrast, there have been noticeable increases in nutrient levels in the Fraser River plume (Strait of Georgia) during the 1970s. The sewage of the city of Vancouver is released near the mouth of the Fraser River. The enriched river runoff forms an enormous, stable surface layer which occupies the middle of the Strait. Nutrient concentrations in the plume were formerly quite low, because of poor mixing with deeper water; now, for the same reason, the nutrients persist, and they may have altered phytoplankton growth in that area.

Excessive phytoplankton growth has become a problem in several areas of Puget Sound into which sewage is released, including Sinclair Inlet and Elliott Bay. Any organic detritus—marine snow, dead plankton, or sewage sludge—will stimulate the growth of bacteria and the consumption of oxygen, and so is said to carry a Biological Oxygen Demand (BOD). While the removal of sludge from sewage reduces the BOD of the waste itself, the remaining nutrients foster phytoplankton blooms, and hence increase the potential BOD. In stratified Budd Inlet off Olympia, the remains of surface blooms sink and are trapped in denser waters near the bottom. Here they decay, consuming enough oxygen to make the water inhospitable and potentially lethal for fish and benthic organisms. In the Duwamish River, furthermore, while sewage may not affect the timing of blooms, it is suspected of supporting an increased phytoplankton standing stock, thus exacerbating a similar problem of decay. The problem arises in these locations because the deeper water is not flushed as thoroughly as in the open main basin, where mixing with surface water at sills maintains a high oxygen level. A similar oxygen shortage troubles the waters off New York City, and may be aggravated by sewage dumping.

The organic matter in sewage effluent may have additional, more subtle effects on water chemistry. Many of the compounds can chelate heavy metals, and may be altering the species composition of phytoplankton in some areas (see page 101). There is also concern about another element in sewage, the dissolved chlorine gas added as disinfectant at levels of about one part per million. Plenty of chlorine is already present in the Sound as sodium chloride (salt), and the chlorine gas dissolved in sewage effluent is diluted 140-fold before it is discharged into the water. Yet doubts persist because both chlorine and its sibling halogen, bromine, are suspected to combine with organic compounds in sewage to form organochlorines and organobromines, which are toxic to plankton at far lower concentrations than the elements alone.

Perhaps the most serious chemical insult inflicted on Puget Sound from sewage outfalls comes from the quantities of other pollutants that are dumped, accidentally and otherwise, down sewers. Metals, petroleum, and synthetic organic chemicals are present in high concentrations in municipal sewage, and are not always effectively removed by treatment. These compounds may also reach the Sound through storm sewers, which can empty urban runoff directly into both Lake Washington and Puget Sound, without even primary treatment, during heavy rains. These pollutants are discussed individually below.

In 1981, METRO, the agency responsible for King County's sewage disposal, was told by the Washington Department of Ecology that the Duwamish River could no longer handle the effluent from the secondary treatment plant in Renton. Already contributing 25 percent, it was feared that sewage effluent could increase to 50 percent of the river's volume during the late-summer low-flow season as a result of population growth east of Lake Washington. METRO planned to bypass the river, where water quality was a problem, and pipe effluent directly into the Sound at a deepwater site off Seahurst Park between Burien and Vashon Island. The impact of such disposal of sewage effluent depends on the flushing rate of the discharge area. Critics disagreed with METRO's siting choice, advocating instead a costlier but possibly better-flushed site near Duwamish Head. METRO hired consultants for an extensive study of the subject, and also obtained a waiver of the federal requirement for secondary treatment of other existing saltwater discharges, intending instead to spend its money on preventing discharge of untreated storm sewage.

Pulp and Paper Wastes

The earliest serious pollutant on Puget Sound was the effluent from pulp and paper mills, once scattered from the southern Sound near Shelton to Everett, Anacortes, Bellingham, and Port Angeles. Two processes are used to digest wood fiber chemically into pulp: the kraft process generates large quantities of sodium hydroxide (lye), sodium sulfate, and sodium sulfide, while the sulfite process releases calcium, ammonium, or magnesium bisulfite. Except for sulfide, found only in anoxic water, the quantities of these chemicals present naturally in seawater are not significantly altered by the pulp effluent.

Accompanying them, however, are dissolved organic compounds leached from the wood, including organic acids and their salts (similar in composition to soap), sugars, and lignins. These can have a number of effects. The leachate can be chemically poisonous either directly by acidifying the water, or by combining, like sewage, to form chelated or organochlorine complexes. The leachate can also deplete the oxygen content of seawater. It consumes oxygen directly by chemical action, and although some leached compounds, as well as some detergents also present in pulp effluent, may stimulate phytoplankton growth at low concentrations, the deep brown color of kraft effluent is suspected of suppressing the oxygenating effects of photosynthesis in seawater into which it is discharged. These effects are detectable only at effluent concentrations of a few percent or more, and though such effects have been observed, notably in British Columbia, pulp effluent nevertheless is one of the least toxic of pollutants.

Pulp and paper wastes are problems on Puget Sound only in locations where they have accumulated due to poor mixing. This unfortunately has been the case at most mills. A plant at Anacortes discharges into a well-flushed channel, but at Port Gardner (Everett), Bellingham Bay, and even off Port Angeles where circulation is restricted by Ediz Hook and Dungeness Spit, waste lingers close to its source. Under state government orders, the problems have been reduced since the early 1970s by chemical treatment, reduction in the volume of effluent, and transfer of release points to better-mixed locations.

The most visible effect of pulp mill effluent on plankton in Puget Sound has been the reduction in zooplankton populations in affected areas. Animals such as euphausiids and juvenile and adult fishes (especially the migratory salmon) avoid areas like Everett Harbor and Port Gardner where effluent concentrations are high. They do return, however, when conditions improve.

The worst damage inflicted by pulp waste apparently strikes animal larvae, especially oyster larvae. The once-rich oyster beds in the neighborhood of Port Gardner have shrunk since pulping began. Oysters and their larvae are at a disadvantage in accommodating pollution, as are many plankters, partly because they cannot avoid tainted areas. The toxicity of Port Gardner surface waters to oyster larvae has dropped in recent years, which may herald a recovery. But the example is a reminder that not all species are equally hardy. Larvae—especially oyster larvae—are among the organisms most susceptible to all types of pollutant stress. For this reason, scientists evaluate the toxicity of waters in Puget Sound by studying their effects on larval oysters, in a procedure called a bioassay. The marine equivalent of laboratory mice, larvae are grown side-by-side in clean water and in water to be tested for pollutant effects, of which deformity or death of the plankters is a measure.

Petroleum

Petroleum pollution of seashores is highly publicized, but its effects on plankton have received less attention. Crude oil is a complex and highly variable mixture of liquid hydrocarbons, each with a different chemical structure and a different weight, grading all the way from light, volatile gasoline to heavy tar. The components that separate during the process of refining also separate when crude oil is spilled on water. What we see on birds and beaches is the heavy fraction, most of which eventually sinks to the bottom. An unseen fraction, containing the lighter hydrocarbons (especially the aromatic hydrocarbons related to benzene and toluene) is far more toxic to marine life. Crude oils from different locations vary in composition and toxicity, but most of the petroleum products refined for people's use—gasoline, lubricating oil, diesel and home heating fuel—are rich in the light fraction, and so are more toxic than plain crude oil. When spilled onto seawater, much of this lighter fraction evaporates, sinks to the bottom, or is decomposed by bacteria, but depending on the conditions—wind, waves, etc.—some of it also dissolves. The invisible dissolved compounds pose the principal threat to plankton.

The major sources of petroleum input to the seas are also nearly invisible. The highly publicized tanker accidents (which Puget Sound fortunately has been spared so far), together with the flushing of bilges, account for no more than a third of the petroleum entering the world's oceans. Nearly the same amount is suspected of entering the sea naturally, through submarine seeps.

Puget Sound is primarily affected by invisible sources of petroleum. Over half of the petroleum that eventually reaches the sea was originally discharged on land as unburned petroleum from automobiles and furnaces, and as domestic, municipal, and industrial waste. Although figures are unavailable on petroleum inputs to Puget Sound, over two-thirds of the oil used in the state of Washington ends up spread on roads, dripped from cars, dumped onto the ground, and carried by rainfall into sewers, rivers, and lakes, and into the Sound. Sewers cannot separate oil from waste water. Half of all the hydrocarbons entering Lake Washington run directly off streets and bridges, amounting to nearly 30 metric tons (33 long tons) a year. Much of the input comes during storms, when some runoff is discharged, untreated, through storm sewers. In Lake Washington and elsewhere, the overwhelming proportion of this petroleum is apparently automobile crankcase oil. The real villains of oil pollution are thus ordinary citizens. As yet, however, no effects of such inputs on Puget Sound plankton have been documented.

Numerous laboratory studies have demonstrated the toxicity of petroleum components to phytoplankton, zooplankton, and larvae, although low levels of hydrocarbons can stimulate phytoplankton growth. The results of field studies of plankton populations near oil spills (Table 7.1) are ambiguous: changes are difficult to detect, and long-term depletion is rarely observed. Although plankters cannot swim away from a contaminated area, as fish can, in most areas their abundance and regenerative capacity are apparently sufficient for rapid recovery. Spills can be devastating, however, for larvae of animals that spawn only once a year, and especially for fish larvae that concentrate at the surface where oil slicks linger. Nevertheless, the difficulty of drawing such conclusions given the inherent quality of oceanographic data must be emphasized. Special care must be taken to distinguish oil from natural plankton hydrocarbons. An interesting sidelight (discussed below) is the possible important role of plankton in removing oil from surface waters to its final resting place on the bottom.

Heavy Elements

All the elements found in nature—and now a few that have been created by technology—are present in the ocean. The composition of natural chemicals dissolved in seawater has, so far as science can determine, reached a steady state in which processes of removal to the sediments just balance the input from rivers. Certain of these elements are harmful in small doses, especially heavy metals such as mercury, cadmium, silver, nickel, lead, arsenic, copper, chromium, and zinc (in decreasing order of toxicity). Some—copper and zinc, as well as iron, magnesium, manganese, molybdenum, and cobalt—are essential to life in small doses, but in higher doses are toxic.

Although the natural concentrations of these elements in seawater are low, the sea is so huge and the turnover of elements so vast that (with the possible exception of lead) it is difficult for humans to add significant amounts. People can make their presence felt, however, by creating new elements, or by dumping large quantities of an element into a small, poorly mixed region, in a form not easily dispersed. Although the levels of heavy elements in Puget Sound as a whole are still very close to the background levels present in the open sea, some potentially harmful metals can be found in elevated concentrations at certain locations (Figure 7.1).

Heavy metals illustrate well that sources and fates of pollutants must be known in order to gauge their effects on plankton. A principal human source of metals in Puget Sound, for example, is the American

Table 7.1 Observed effects of oil spills on plankton. Although data on the impacts of spilled oil on plankton are scarce, they suggest greater resistance and powers of regeneration in the plankton than among plants and animals of the seashore where oil is trapped.

Spill	Phytoplankton	Zooplankton	Source
Torrey Canyon England, 1967	Some mortality	No data	Malins (1977)
	No data	Fish eggs and larvae mortality	GESAMP (1977)
Santa Barbara, 1969	No mortality observed	No data	Middleditch (1981)
Florida Buzzards Bay, Massachusetts, 1969	No data	Reduction in crab larvae survival for several years	Krebs and Burns (1977)
Refinery Seto Inland Sea, Japan, 1974	No visible effect	No visible effect	American Petroleum Inst. (1979)
Argo Merchant Cape Cod, 1976	No data	Reduction in biomass	Malins (1977)
	No data	Contamination	American Petroleum Inst.(1979)
Sansinena explosion Los Angeles, 1976	Temporary depletion, physiological stress	Temporary depletion, species changes	Geyer (1980)
Tsesis Swedish Baltic, 1977	Increased biomass, probably due to reduced grazing	Temporary local drop in biomass, heavy contamination	Kineman et al. (1980)
Ekofisk North Sea, 1977	Little effect	No data	Lannergren (1978)
	No data	Contaminated	Mackie et al. (1978)
Amoco Cadiz Brittany, 1978	No data	Mortality highest and recovery slowest near shore	American Petroleum Inst. (1979)
	No data	Chronic depletion in places	Spooner (1978)
IXTOC Gulf of Mexico, 1979-80	Large blooms	Mortality	Jernelov and Linden (1981)
Tidal test pond, Mississippi coast	Primary production drops 50%, recovery in 2 months	Immediate mortality, recovery within 6 months	Brown (1980)

Smelting and Refining Company (ASARCO) smelter in Tacoma. From this plant, arsenic, a by-product of copper smelting, is recovered and sold commercially. It is also dumped into Commencement Bay as crystalline slag and discharged as arsenite dust into the atmosphere and as liquid into the Sound. Arsenic is harmful to organisms because it can masquerade as the essential nutrient, phosphorus. The effects of the smelter on the Sound, however, are less than they might appear. The crystalline slag is poorly soluble in seawater, and the air- and water-borne arsenic, together with a lesser amount of natural arsenic which enters the Sound via river runoff, is very soluble. The strong mixing and flushing action of the Sound rapidly disperses the human input, and dissolved arsenic levels are elevated above background levels only in the immediate vicinity of the smelter and in the Tacoma tideflats, where slag was used for landfill.

A different pattern is exhibited by the metal mercury. While relatively innocuous in its elemental form as a liquid metal, mercury in ionic form (and particularly compounded in an organic molecule) is a potent toxin. The "Minamata Disease," a complex of neurological symptoms including visual and cognitive impairment, paralysis, and birth defects, was named for a Japanese bay from which local cats, birds, and humans consumed large quantities of seafood contaminated by factory discharge of mercury. Dangerous toxicity resulted when this mercury was compounded into an organic form.

Until 1970, a chlor-alkali plant on Bellingham Bay released five to ten kilograms of liquid (metallic) mercury per day as a by-product of the manufacture of chlorine gas and lye. This amount far exceeded the bay's natural inputs of dissolved ionic mercury, a few ounces per day, from rivers and the atmosphere. Flushing carried another five to ten kilograms per day of dissolved mercury in and out of the bay, the natural background in seawater. At their peak, dissolved mercury concentrations reached one part per billion near the outfall, but were diluted back to background levels of ten parts per trillion by the time water exited from the bay. Most of the mercury adhered instead to particles, and sank to the bottom, where much of it remains and conversion to organic form can occur. Thus, there was less of a threat to plankton than to benthic animals. Similar problems with mercury have occurred in the Strait of Georgia, but neither condition has approached the seriousness of the situation at Minamata.

Another source of metals in Puget Sound is sewage. Peak metal concentrations, caused by intermittent dumping of waste into the sewage system, have reached 800 parts per billion of copper, 100 parts per billion of lead, and 9 parts per billion of cadmium, in undiluted effluent from the West Point Treatment Plant, 10 to 100 times their background levels in the Sound. Cadmium and lead concentrations in effluent exceed safety standards specified by the Environmental Protection Agency. The potential threat is reduced, however, by dilution of the effluent before discharge and by vigorous flushing at the discharge site.

Extreme caution must be exercised when using such numbers to pinpoint possible environmental threats. In Puget Sound, the mass of metals in sewage effluent is so small compared to that in the natural seawater flow in the Sound, and to other inputs of metals to the Sound, that levels of dissolved metals show little variation within the Sound, or between the Sound and offshore waters. Technology for measuring metals is also evolving rapidly, and in some cases previous measurements have been a hundredfold too high. Furthermore, the strong interaction of metals with suspended particles of all kinds, including plankton, affects their presence in water and in organisms, and contributes to their ultimate deposition in the sediments. There is evidence, in fact, that particulate rather than dissolved metal concentrations control toxicity to plankton.

Some paradoxes and confusion over the possible effects of metals are linked to the chemical states of the elements in question. Different workers have found natural zinc concentrations in the North Atlantic to be alternately insufficient and excessive for phytoplankton growth, and there is also speculation that natural concentrations of copper may be inhibitory. Dissolved metals usually reach salt water in the form of compounds, and the nature of a compound will influence both its fate in seawater and its toxicity to plankton. Like mercury, lead is more toxic as an organic compound. Excess lead in Puget Sound comes mainly from automobile exhaust, in a tetraethyl compound. Transformations of metals into compounds of differing toxicity can be mediated by plankton. Effects of a single metal can also be complicated by the presence of others, a common situation in polluted environments.

Metallic ions in water can also couple themselves loosely and reversibly to complex organic molecules in an association known as chelation. In this state they are apparently less free to interact with other chemicals or with organisms, and their biological effects will depend in part on the amount remaining free in solution. Among the organic chemicals that may act as chelators are those in soil runoff, sewage, and pulp mill effluent, as well as some compounds released by plankters themselves. Methods to measure chelation so far are unreliable. There has been speculation that red tide phytoplankters are more sensitive to metal pollution, and that red tides are increasing in frequency because chelators in sewage protect the organisms from inhibitory amounts of metals present naturally in the sea. Much evidence conflicts with this hypothesis, however; the complexity of the effects of pollutants on phytoplankton species will be demonstrated when the CEPEX food-web experiments and red tides are examined (Chapters Seven and Eight).

Heavy radioactive elements from nuclear reactions (from bomb tests and power plants) have been judged one of the worst potential ocean pollutants. Although some radionuclides are relatively abundant in the sea, others (some of which have an affinity for living tissue) are rare and could be significantly elevated—at least locally—by human activities. Considerable study has been devoted to the coastal waters off Washington and Oregon where radionuclides from the Hanford nuclear reservation are delivered by the Columbia River. Some of this radioactivity may spread northward into ocean water that enters the depths of Puget Sound, but as yet no harmful impact has been observed either off the coast or here.

Synthetic Organic Chemicals

Perhaps the most insidious pollutants in Puget Sound belong to a highly diverse group of chemicals composed of rings and chains of carbon atoms. They resemble some of the compounds in petroleum, but differ in being entirely anthropogenic (manmade), and having been nonexistent scarcely a generation ago. Their production has skyrocketed in the last few decades, and traces of such chemicals can now be found everywhere in the world, even in the Antarctic ice cap. Up to three million such chemicals are now in commercial production, but most scientists are aware of the names—much less the biological hazards—of only a few.

One of these, valued at first for its toxicity, is DDT, banned for use in the United States since 1970 after it was publicly implicated in reproductive mortalities of such birds as the brown pelican and osprey. DDT became the classic example of a persistent biocide undergoing biomagnification. Locally, such chemicals may be implicated in harbor seal pup mortalities in the southern Sound.

Receiving less publicity, however, are perhaps thousands of related compounds that are released inadvertantly to the environment and washed down, ultimately, to such places as Puget Sound. Many of these are poorly studied and difficult to recognize in the marine environment. Some attention has been paid to the effects in Puget Sound of one family of organic chemicals, the polychlorinated biphenyls (PCBs). Belonging to that class of substances known as halocarbons or organochlorines (in which we also find the by-products of sewage chlorination), PCBs are highly toxic and persistent and make a useful case study for the effects of organotoxins on plankton.

PCBs occur as dense, viscous, inert, clear liquids with varying degrees of chlorination. They are useful as electrical insulators, plasticizers, and lubricants. Although no longer in production, PCBs still in use enter the environment indirectly from such products as electrical transformers, lubricants, rubber, plastic, and paint, as well as directly from spills, such as those in the Duwamish River in 1974 and near Anacortes in 1980. On entering seawater, PCBs sink directly to the bottom, mixing and dissolving little, and soak into the sediments.

Concentrations of dissolved PCBs in Puget Sound are highest in the industrialized waterways near the mouths of the Duwamish and Puyallup Rivers. Although there are high concentrations (up to 400 parts per trillion) in sewage effluent, the major PCB source for the Sound is the huge volume of river water entering the Whidbey basin, with a low level of PCBs from routine leakage and disposal. The major sinks, as for most pollutants in Puget Sound, are removal to the sediments and flushing out to sea.

The more such compounds are investigated, the greater the number found in the marine environment. A laundry list of potential hazards includes hexachlorobenzene, hexachlorobutadiene, pentachloraphenol, phthalates, and a variety of pesticides. Exceeding EPA standards in Seattle sewage effluent are, among others, chloroform, benzene, and pentachlorophenol.

Such organics are as toxic as any marine pollutant, showing deleterious effects on plankton at concentrations as low as one part per billion. The physiological modes of action of such chemicals on plankton are essentially unknown, and are likely to be as varied as their chemical structures. PCBs, for example, inhibit photosynthesis, but to different degrees in different phytoplankton. Recent evidence indicates that at least some PCBs can be broken down and detoxified in nature by bacteria or other causes.

Many such organic chemicals are poorly soluble in water. PCBs, in fact, are also heavier than water and tend to pool on the bottom. This insolubility means that PCBs have fates other than accumulation in seawater. One alternative path is to concentrate in the organic film that, because of surface tension, is found in the upper few millimeters of water. PCB concentrations in this layer have been estimated at five or more times those just below the surface, which can affect fish eggs and other specialized organisms, the neuston and periphyton, living at this interface.

Of all pollutants, organic chemicals have perhaps the strongest tendency to be absorbed by particles in water. Thus the insolubility of toxins, far from protecting plankton, actually makes plankton a major site of pollutant accumulation. As a result, the discussion of pollutant effects on plankton now merges with an examination of the role of plankton in the disposition of pollutants, and especially in the ways higher animals, including people, are affected.

Effects of Plankton on Pollution

In relatively clean waters, such as those of Puget Sound, plankters may actually have more influence on the fates of pollutants than pollutants do on plankton. When the two come in contact, the pollutants may be transposed, transformed, and transported by the plankton, and thus their effects on the rest of the marine food web may be altered or even controlled.

Absorption and Elimination

Figure 7.2 presents the concentrations of selected pollutants in Puget Sound plankton and suspended matter, mussels, and higher animals. When compared to the concentrations of dissolved pollutants (Figure 7.1), it is clear that these chemicals have an affinity for organisms, and selectively concentrate in them by a factor of a thousandfold or more.

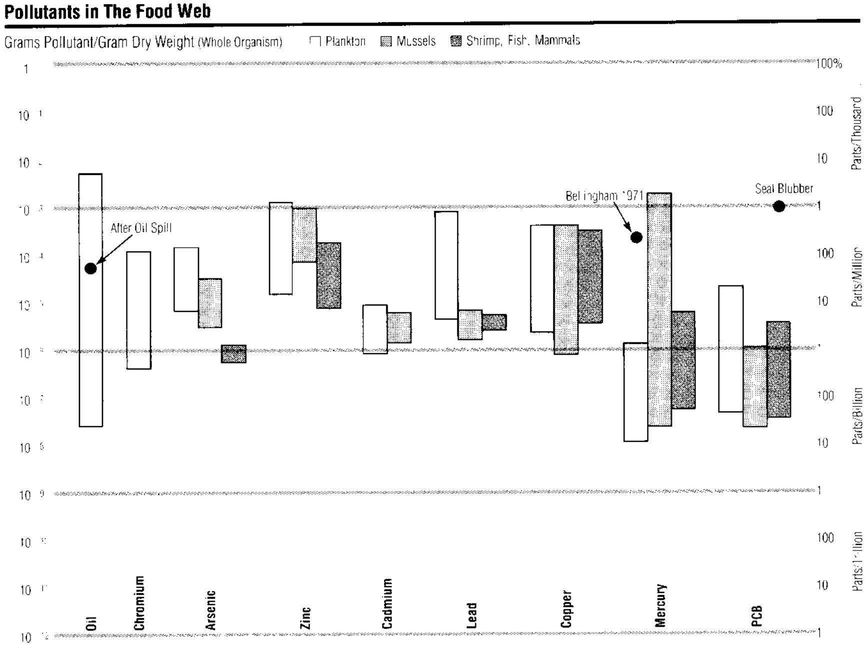

Figure 7.2 Concentration ranges (as a fraction of dry weight, assumed equal to one-sixth of wet weight) of pollutants measured in the tissues of Puget Sound plankton, mussels, and higher animals including fish, other shellfish, and mammals. Concentrations are roughly 1,000 times those in the surrounding water, demonstrating some bioaccumulation. Concentrations are similar at all trophic levels, however, providing little evidence of biomagnification.

This is a demonstration of bioaccumulation, the process by which organisms collect and store chemicals from their environment. The fact of bioaccumulation has been documented beyond any suspicion of analytical errors or experimental artifacts. The causes behind it, however, are both numerous and poorly understood, and data such as those in Figures 7.1 and 7.2 vary widely with season, organism, method of analysis, and location. One hundred parts per million of zinc, five times that of cleaner areas of the Sound, have been measured in plankton off West Point. Copper, at 90 ppm, is nearly 50 times higher in plankton off West Point than elsewhere. The highest levels of metal in plankton have been found at a dredge spoil disposal site in Elliott Bay, where lead at 886 ppm is nearly 200 times higher than in the cleaner plankton of Hood Canal.

Phytoplankters are, of course, specifically adapted for extracting scarce chemicals from seawater; nitrate and phosphate, for example, are present at levels of parts per million. Planktonic plants have evolved large surface areas and active metabolic pathways for taking up and storing nutrients, including such essential trace metals as zinc and copper, as well as such organic compounds as carbohydrates, amino acids, and vitamins. It should be no surprise, then, that toxic metals and organic compounds can be absorbed as well.

Accumulation may not be entirely biological because pollutants are equally concentrated in living and nonliving particles. Chemicals might simply be retained when organisms die and produce detritus, but there is evidence that living and dead particles accumulate at least some chemicals at comparable rates. Radioactive plutonium adheres equally rapidly to the surfaces of living and dead phytoplankton cells, and inert suspended matter from the Skagit River can absorb its own weight in oil. PCBs can transfer from nonliving to living particles. It may be, furthermore, that much of what appears to be uptake of metals into the protoplasm of plankters may simply be the adherence of tiny, colloidal metal particles to the outer surfaces of the organisms. The diatom *Ditylum*, one of the phytoplankters most sensitive to metal poisoning, secretes an outer mucous sheath, which it can slough off along with any pollutants adhering to it.

Part of the driving force for accumulation comes from the poor solubility of many metallic and organic compounds in seawater, and their corresponding affinity for organic matter (especially lipids) and even just inert surfaces. A gram of typical Puget Sound suspended matter, in fact, has a surface area of about 22 square meters. Crustaceans in general have an advantage over other animals because of the protection afforded them against direct absorption of pollutants from water by their exoskeleton, which in addition takes some of the body burden of toxins with it when the animals molt. But crustaceans are particularly sensitive to one class of pollutants, the organochloride insecticides, because of their close kinship with the insects those compounds are targeted to destroy.

The champion bioaccumulators are the filter-feeding bivalves, which even in the absence of their planktonic and suspended food will rapidly draw intense concentrations of pollutants across their gills and into their tissues from the large volumes of water they process. This ability, in fact, has contributed to the use of the common blue mussel, *Mytilus edulis*, as a worldwide early-warning system for marine pollution in a program called "Mussel Watch."

The concentrations of pollutants in exposed organisms and suspended matter do not increase indefinitely, but reach a plateau or saturation point. If placed in clean water, the pollutant burdens will decline. The bioaccumulation process is reversible to an extent; chemicals will migrate from zones of high concentration to low, whether into or out of organisms. Twenty-thousandfold accumulations of PCBs in phytoplankton can disappear after five days in clean water. Zooplankters use fecal pellets to rid themselves of toxins, perhaps even without assimilating them. PCB concentrations in fecal pellets of Mediterranean Sea euphausiids, for example, were 4 to 20 times those in the animals' phytoplankton food, several thousand times the levels in the animals' own bodies, and 1.5 million times those in the surrounding water. Toxins can remain permanently in some body tissues, however, particularly in fat and oil deposits or in nonliving skeletal components.

Transformation

Once associated with suspended matter, living or dead, pollutants do not necessarily retain their original identities. Some compounds, including petroleum hydrocarbons and even DDT and PCBs, are biodegradable. Many bacteria and plankters have the ability to alter or breakdown chemicals foreign to their systems.

Tin has been observed to undergo an organic transformation in plankton off California, which greatly increases its toxicity. Bacteria are implicated in such transformations as the conversion of the inorganic mercuric chloride emitted from the manufacturing facility on the shores of Minamata Bay, Japan, into organic methyl mercury, which has a thousandfold higher affinity for living tissue and a similar increase in toxicity. To that extent, those microorganisms shared the blame for the tragedy that resulted. The same process operates in the sediments of Bellingham Bay.

In contrast, however, bacteria and phytoplankton in Puget Sound convert inorganic arsenic compounds (which behave much like phosphate nutrients) to organic compounds, which are less toxic. There is also speculation that the unexplained liberation of dissolved organic compounds by phytoplankton may be a strategy to introduce chelators into the water, and so to tie up any potentially inhibitory metals.

More intriguing, however, are some of the mechanisms plants and animals use to cope with their internal body burdens of pollutants. Marine diatoms have been observed to break down DDT. Copepods from the vicinity of oil spills have been found to synthesize an enzyme (benzo (a) pyrene hydroxylase) that can dismantle one of the more toxic components of crude oil, and which is produced in response to the presence of oil. Phytoplankton and copepods contain a protein called metallothionein which can absorb and detoxify a certain quantity of metals. It appears, however, that these metallothionein-bound metals are not eliminated as quickly when organisms are placed again into clean water.

Transportation

The accumulation of pollutants in suspended matter, including plankton, merits special consideration because pollutant and particle thenceforth share the same physical fate. As the ultimate fate of most particles is to sink to the bottom (passing through various incarnations, living and dead), so many pollutants wind up buried in the sediments.

The extent to which suspended matter governs the fate of a particular pollutant depends on its relative affinities for water and particles. It is estimated, for example, that 40 to 90 percent of such poorly soluble pollutants as petroleum and mercury will come to rest in sediments, compared to less than 10 percent of the more soluble copper and cadmium. The removal of dissolved arsenic to the sediments is estimated to be 15 percent, mostly by adsorption onto clay.

Particles control the fate of poorly soluble pollutants despite bearing, at a given time, only a small fraction of the Sound's pollutant burden. Although pollutant concentrations in Puget Sound suspended matter may exceed those in water by a thousandfold or more, there are also at most nine parts of particles to a million parts of seawater. Nevertheless, the turnover of particles is so rapid that the constant replacement of this small fraction dominates other pollutant removal processes. Although it contains 20 percent of the PCBs in the Sound at a given time, for instance, sinking suspended matters removes to the sediments 80 percent of the Sound's dissolved PCB income. There is, in general, a good correlation between pollutant burden in suspended matter and in sediments at the same location.

The most important mechanism for delivering particles and the pollutants they contain to the bottom is the generation of fecal pellets by zooplankton. Copepods near a tanker accident off Nova Scotia were observed to ingest whole oil droplets without harm to themselves, eliminate them intact in their fecal pellets, and in so doing quickly deliver to the sediments 20 to 30 percent of all the oil spilled. Molted exoskeletons and dead carcasses also carry pollutants bottomward.

Thus,the importance of the transfer of pollutants from dissolved to particulate form is twofold. The accumulation of pollutants into the tissues of plankton, and the possible biomagnification at higher trophic levels, provide an avenue by which pollutants are channeled into fish and marine mammals to cause possible harm to them and to humans. But the greater effect of the same phenomenon may actually be a preventive one, from the point of view of the pelagic food chain—it may extract pollutants from the water and shunt them downward, out of the reach of pelagic animals, and into the sediments. Though a boon for the pelagic food chain, this bottomward diversion might have serious consequences for benthic animals, many of which are also important to the human economy. Much publicity has focused, for instance, on the health of bottomfishes in urban areas of the Sound.

Pollution and the Food Chain

Perhaps the greatest threat of pollutants to natural ecosystems, aquatic or terrestrial, is the potential for biomagnification of toxins from prey to successive predators, their effects worsening at each link of the food chain. The origin of the modern environmental movement can be traced to the discovery that birds, at the top of the food chain, suffered from pesticides directed at other organisms. Years of intense research since then have, as scientific inquiries often do, provided as many questions and exceptions as answers—especially in the marine environment, which behaves quite differently than the land. That biomagnification can occur under certain circumstances is not seriously disputed, but there is doubt and controversy about its importance relative to other pollution phenomena.

Pollutant concentrations in the tissues of animals at higher trophic levels in Puget Sound were presented in Figure 7.2. Biomagnification of mercury has been observed elsewhere in the large, predatory, and long-lived Atlantic swordfish, in the Pacific sperm whale, and in tuna. Museum specimens indicate that the former two species accumulated mercury long before humans began adding it to the environment. Mercury levels in most Puget Sound dogfish exceed the U.S. Food and Drug Administration standard of 0.5 parts per million for human consumption, so the catch must be exported. The high PCB levels in southern Sound harbor seals have the appearance of classic biomagnification, and have been tentatively linked to increased pup mortality in that location, as well as in southern California and in the Baltic Sea.

Several factors complicate the simple picture of increasing pollutant burdens at higher trophic levels caused by uptake from food. These include the exchange of pollutants directly with the water (or sediment), the abilities of organisms to transform and eliminate pollutants, and the peculiarities of individual chemical and biological species. Magnification patterns are also complicated by the varied diets, life cycles, and migratory patterns of plankton and higher animals.

Many field tests of biomagnification have met with mixed results. As evident from Figure 7.2, pollutant levels in some higher organisms in Puget Sound, including such planktivores as fish and shrimp, can be lower than those in plankton, which ostensibly occupies lower trophic levels. In such comparisons the artificial concepts of "food chain" and "food web" begin to lose their utility, for in the maze of dietary connections in Puget Sound, trophic levels blur. Attempts to test for biomagnification by tracing increases in nonpollutant elements (specifically, the ratio of cesium to potassium) at higher trophic levels in a food web off California have proven inconclusive as well. The highly publicized fish diseases in urban areas of the Sound can be caused by direct contact with contaminated sediment, and so do not necessarily result from biomagnification at all.

The occurrence of biomagnification, and its importance relative to other modes of contamination of organisms, seems to depend on the relationships of various types of pollutants and organisms to water. Pollutants that are poorly soluble in water (hydrophobic) and more soluble in fat (lipophilic)—including petroleum, chlorinated hydrocarbons, and mercury—are more likely to be bioaccumulated in living tissue, as well as in detritus and organic sediments. They are partitioned from water and retained in lipid tissues, and are difficult to excrete unless chemically transformed. Such pollutants tend to accumulate most in organisms that live the longest, and which have a higher fat content, such as dogfish and harbor seals. Such pollutants likewise have a higher potential for transfer up the food chain, and thus for biomagnification.

There are also differences between animals based on the degree of direct exposure of their tissues to water. Gilled animals, especially those that pump water to feed, are likely to have higher rates of pollutant exchange (both uptake from and elimination into ambient water) than animals with impermeable body surfaces. Thus rates of pollutant exchange would be higher in suspension-feeding bivalves than in carnivorous fishes, and higher in either of those than in air-breathing marine birds and mammals. A faster rate of exchange implies that observed body burdens of pollutants result from simple bioaccumulation from water, rather than from biomagnification. Animals at the tops of marine food chains, especially birds and mammals, exhibit the greatest biomagnification because of their long life spans, their high fat contents, and their reduced ability to exchange acquired toxins with the water, as well as because of their higher trophic status.

The differential effects of pollutants on various species have an important manifestation in Puget Sound plankton, as revealed by studies in neighboring waters. A major study in Saanich Inlet, B.C., tested the effects of addition of oil, PCBs, copper, and mercury to large plastic cylinders of seawater. The study was called CEPEX, for Controlled Ecosystem Pollution Experiment. The CEPEX study found that these pollutants did more than simply reduce the standing stocks of plankters or inject toxins into the food chain. Pollutants selectively crippled the diatom-based primary food chain, that collection of plankters thought to favor the growth of salmon and other valuable pelagic fishes.

There is evidence from elsewhere in the sea, as well as from CEPEX, that large, centric diatoms are the most sensitive phytoplankters to all kinds of pollutant stress. In studies from Long Island Sound, New York, the diatoms *Skeletonema*, *Thalassiosira*, and *Chaetoceros* suffered reduced growth at PCB concentrations as low as one part per billion, while the pennate diatom *Nitzschia* and the green flagellate *Dunaliella* were unaffected by levels of up to 100 parts per billion. Centric diatoms are sensitive to concentrations of 50 parts per billion of DDT, while *Dunaliella* is resistant to one part per million. Similar results were found with the insecticides Chlordane and Dieldrin, with the latter selectively eliminating phytoplankters larger than a certain size. Laboratory experiments parallelling CEPEX showed that low levels of petroleum hydrocarbons (50 parts per billion) selectively stimulated the growth of phytoflagellates and small pennate diatoms, the same groups that populate Saanich Inlet during off-bloom periods. Zooplankton groups may also differ in their sensitivities to pollutants, but such effects are difficult to distinguish from effects of altered phytoplankton diet.

The most conclusive results, however, came from CEPEX itself. When copper was added at 50 parts per billion, large centric diatoms were replaced by an equivalent biomass of phytoflagellates and small pennate diatoms, the base of the secondary branch of the food web. This replacement happened in unpolluted enclosures, but the effects were more pronounced under copper stress. The surviving organisms demonstrated a tolerance to high levels of copper, compared to untreated organisms of the same species. The addition of copper also stimulated a rapid increase in the release of organic carbon by phytoplankton, and a subsequent explosion in bacterial populations, supporting the suspicion that such "excretion" may be a deliberate behavior to reduce metal toxicity by chelation. The small phytoplankters could no longer be harvested by the large zooplankton present, which in addition suffered some direct toxicity from the copper, and so died off.

Different results were obtained when one and five parts per billion of methylmercury were added to enclosures containing fresh experimental populations. An initial period of drastic decline in phytoplankton populations was followed by a recovery, with some demonstration of an acquired tolerance to mercury. The population to which one part per billion had been added grew back as the predicted small flagellates, but large diatoms and dinoflagellates dominated the recovery in the more polluted enclosure, and productivity after two months exceeded that in the unpolluted enclosure—hardly what would be expected from severe pollution.

At five parts per billion, mercury appeared to affect the zooplankton more than the phytoplankton. When mercury was added, the copepods *Calanus* and *Pseudocalanus* and their larvae disappeared, leaving the larvacean *Oikopleura* as the dominant zooplankter. With the small phytoplankton removed by *Oikopleura* and the copepods removed by mercury, the large diatoms and dinoflagellates were free to bloom without interference. The copepods, furthermore, were never able to recover because their nauplii could not survive without small phytoplankton. Finally, juvenile salmon inhabiting the enclosure, while not directly affected by the mercury, starved for lack of copepods to eat.

These results demonstrate the complexity of pollutant effects, and illustrate indirect damage to animals by elimination of their food supplies when no direct toxicity is present.

The conclusion distilled from all this is that the effects of pollutants on the planktonic food chain, and on the higher animals that depend on that food chain, cannot be interpreted in any simplistic fashion. There are direct toxic effects of pollutants on both plants and animals. Biomagnification can occur as toxins pass from prey to predator, but serious consequences seem limited to particular pollutants and specific animals. When overall primary productivity is reduced as a result of pollution, animals can be affected by reduced food (and perhaps oxygen) supply. But changes in the quality of food supply can be as catastrophic as reductions in quantity; animals cannot exploit an improper food, however abundant that food may be. The most significant consequence of polluting the plankton might be a shift away from the normal population balance, toward some unknown new community, with unpredictable results on the food web.