MEMORANDUM TO THE PRESIDENT

From: **Andrew R. Solow**

Subject: **Red Tides and Dead Zones: Eutrophication in the Marine Environment**

PROBLEM

The most widespread and economically costly chronic pollution problem along the world's coasts is eutrophication. Eutrophication occurs when high levels of chemical nutrients stimulate excessive growth of aquatic plants. There is a clear connection between eutrophication and two significant marine environmental problems: the occurrence of harmful algal blooms and the depletion of dissolved oxygen in bottom waters. Harmful algal blooms pose a threat to human health and to commercial and recreational activities at the coast, while oxygen depletion or hypoxia poses a threat to fisheries. Beyond these direct effects on human welfare, both harmful algal blooms and eutrophication can have profound effects on marine food webs and biological diversity. Certain types of harmful algal blooms can destroy ecologically important habitats like seagrass beds and coral reefs, while others can cause illness and death in marine mammals. Oxygen depletion associated with eutrophication can reduce the diversity of biological communities on the seafloor.

BACKGROUND

In the ocean, as on the land, photosynthesis combines energy from the sun, carbon dioxide, and chemical nutrients like nitrogen and phosphorus to produce carbon-rich plant material. This natural process, which is called primary production, forms the base of the marine food chain: without it, the ocean could not support life. However, human activities—notably, the intensification of agriculture; the disposal of human and animal waste; the conversion of riverine, estuarine, and coastal ecosystems; and the combustion of fossil fuels—have increased the discharge of nutrients to coastal waters above its natural level, causing excessive primary production. This is called eutrophication. Although eutrophication is a regional problem, in the sense that its causes and effects tend to be localized, it is also a global problem, in the sense that it occurs along all of the world's inhabited coastlines. The effect of growing nutrient levels on primary production is felt throughout marine ecosystems. As these ecosystems provide commercial, recreational, and other benefits, eutrophication also has effects on human society.

. . .human activities—notably, the intensification of agriculture; the disposal of human and animal waste; the conversion of riverine, estuarine, and coastal ecosystems; and the combustion of fossil fuels—have increased the discharge of nutrients to coastal waters. . . .

Eutrophication and its associated effects pose a difficult problem in environmental policy. The activities that contribute nutrients to the marine environment are many and varied. The physical and biological processes linking these nutrients to eventual effects are complex and scientific understanding is incomplete. In contrast to the economic value of the activities that produce nutrients, much of the damage due to eutrophication accrues to recreational activities, environmental quality, and biological diversity, so it is difficult to measure in economic terms. Despite the widespread nature of this problem, when measurement is possible, as with the effects on public health and commercial fisheries, these damages appear to be relatively small in aggregate terms, although they can be substantial locally and, unless steps are taken, are likely to grow over time. Taken together, all this suggests that policy makers should begin by looking for measures that reduce nutrient discharge at low or no cost and that have other benefits to society. Two such measures are the use of so-called best management practices in agriculture to reduce the loss of fertilizer and the restoration of wetlands and other buffers to intercept nutrients. In addition, a system for managing growing concentrations of animal wastes needs to be established. Finally, reducing the atmospheric deposition of nitrogen in the marine environment provides an additional rationale for a range of air quality measures.

Harmful algal blooms

There are several thousand species of marine algae. These can be divided into microscopic species, called microalgae, and larger macroalgae, commonly known as seaweeds. Perhaps 100 species of microalgae contain potent toxins. Because high concentrations of some of these species can color the water red or brown, they are sometimes referred to as red or brown tides, although these terms are misleading and are no longer used by scientists. Toxic algae enter the marine food chain when it is consumed by certain kinds of fish, shellfish, and small marine animals called zooplankton. The toxins that accumulate in these consumers are then passed up the food chain to fish, marine mammals, and eventually to humans, where they can cause illness or occasionally death. In the United States, most human illness caused by toxic algae occurs when contaminated shellfish are consumed. These illnesses are collectively known as shellfish poisoning and can cause an array of symptoms from temporary gastric disturbance to permanent neurological damage. In addition to shellfish poisoning, in warmer regions, ciguatera poisoning can occur from ingesting contaminated reef fishes. Toxic algae can cause illness and death in fish, such as in the widely-reported 1991 outbreak of pfiesteria poisoning in the Pamlico River of North Carolina, and pose a particular threat to cultured fish raised in cages and pens. Toxic algae have also been implicated in the deaths of marine mammals, including seals, whales, and dolphins.

Although less dramatic than the effects of toxic microalgae, macroalgae can also cause problems. Large blooms of macroalgae can coat beaches, interfering with recreational activities. Macroalgae can also clog or destroy seagrass beds and coral reefs that provide nursery grounds for commercially important fish and, more generally, support high levels of biological diversity.

Harmful algal blooms occur in every part of the world. In the United States and other developed nations, monitoring efforts and shellfish closures have reduced the incidence of human illness caused by toxic algae. However, both monitoring and closures have economic costs that can be locally substantial. Perhaps the most striking example in the United States is the complete loss of the Alaska wild shellfish resource, which once produced 5 million pounds annually, to persistent paralytic shellfish poisoning. In less developed parts of the world, human illness from the consumption of contaminated fish and shellfish remains a threat to public health. For example, reported cases of ciguatera poisoning currently number about 50,000 annually throughout the world and it is widely believed that the majority of cases go unreported.

It is difficult to assess the role played by human activities in the occurrence of harmful algal blooms. The difficulty stems from the complexity of the physical and biological processes involved and the relatively sparse record of observations. However, while harmful algal blooms can and do occur in relatively pristine conditions, there is a clear relationship between nutrient levels and primary production and it is generally agreed that, other things being equal, factors that favor high levels of primary production also favor harmful algal blooms. Although the observational record is sparse, there is much in it to support this conclusion and little or nothing to contradict it. Beyond the direct effect of increasing nutrient levels on primary production, it has been suggested that the mix of nutrients produced by human activities—predominantly nitrogen and phosphorus, with a little silica—may favor the phytoplankton group with toxic members over less toxic groups.

Hypoxia

The term hypoxia refers to the depletion of dissolved oxygen in ocean bottom waters. In technical terms, hypoxia is said to occur when dissolved oxygen falls below 2 milligrams per liter. Hypoxia occurs when organic material, in the form of dead phytoplankton cells or fecal pellets from predators of phytoplankton, falls to the bottom and is decomposed by oxygen-utilizing bacteria. As long as the bottom waters are well mixed with the oxygen-rich surface waters, the oxygen used by decomposers is renewed. However, under certain conditions, the water column is stratified and there is little mixing. Stratification tends to occur during the summer, when warming at the surface is strongest. The configuration of warm water overlaying cold water is stable and resists mixing. Stratification also tends to occur near the mouths of rivers, where the stable configuration of lighter freshwater overlaying heavier salt water also resists mixing. Finally, stratification is stronger in enclosed or semi-enclosed water bodies that are cut off from large-scale oceanographic processes that promote mixing. When mixing is weak or absent, the oxygen used in decomposition cannot be renewed and hypoxia can occur.

Because animal life depends on the availability of oxygen, the occurrence of hypoxia can have a dramatic effect on marine organisms. The response of marine organisms to hypoxia is varied. Immobile or slow-moving organisms may simply suffocate. While mobile organisms, such as shrimp, lobsters, and fish, can often avoid the direct effects of hypoxia, there can be serious indirect effects. By itself, the loss of once-suitable habitat and the prey that it contains means that the area can only support smaller populations. If all suitable habitat is eventually lost, then the entire population will vanish as well. The occurrence of hypoxic zones can interfere with the offshore migration of animals like shrimp and lobsters. This can delay development and increase predation risk. In extreme cases, hypoxic conditions can trap large numbers of animals in shallow waters, resulting in massive fish kills. Beyond direct damages to economically important species, the occurrence of hypoxia can completely alter the biological community inhabiting the sediments on the ocean floor. Not only is biological diversity lost in this so-called benthic community, but even when the hypoxia itself is broken up by wintertime mixing and commercially important species return, the alteration of the benthic community on which they feed can affect their growth and development.

While the effects of extreme hypoxic conditions on marine species are fairly clear, the effects of less extreme conditions are more difficult to discern. For example, there is an inverse annual correlation between the areal extent of summertime hypoxia and size of shrimp stocks in the northern Gulf of Mexico. However, a similar correlation exists between the areal extent of hypoxia and the size of shrimp stocks outside the hypoxic zone. A possible explanation is that the same regional climatic conditions that favor hypoxia—specifically, high spring rainfall that increases the discharge of nutrients from the Mississippi River system into the Gulf—also have an adverse effect on young shrimp in estuarine nursery areas throughout the Gulf region. Even if this is the case, there is little doubt that continued growth of hypoxia in the Gulf would eventually have an adverse effect on shrimp and other economically important species.

Hypoxia occurs throughout the world. Two of the best known hypoxic areas are in the Black Sea and the Baltic Sea. In the United States, the best known areas of hypoxia are Long Island Sound, the Chesapeake Bay, and the Louisiana Gulf coast (where it is popularly known as the "Dead Zone"). Although there is considerable variability from place to place and observations are limited, there is no doubt that hypoxia has effects on fisheries. In the Black Sea and the Baltic Sea, hypoxia has contributed to the replacement of demersal (i.e., groundfish) fisheries by less profitable pelagic (i.e., mid-water) fisheries. By living up in the water column, pelagic fish are generally unaffected by hypoxia in bottom waters. Also, many pelagic fish prey on phytoplankton and may actually benefit from high levels of primary production. Hypoxia has contributed to the collapse of the Norwegian lobster fishery and the displacement of lobsters in Long Island Sound. Although the hypoxic zone along the Louisiana Gulf coast is large, it has not reached the level of severity seen elsewhere. Nevertheless, there is already some evidence of effects on the important shrimp fishery and a possible replacement of demersal species, like snapper, by pelagic species, like menhaden.

Hypoxia can occur naturally. For example, the bottom waters of the Black Sea have experienced total depletion of oxygen (which is called anoxia) for thousands of years. Naturally occurring hypoxia has occurred in the Chesapeake Bay and along the Louisiana Gulf coast. However, there is no doubt that, by increasing the level of nutrients in surface waters, human activities have increased the frequency, areal extent, and severity of hypoxia in these areas and throughout the coastal environment.

RECOMMENDATIONS

For a variety of reasons, determining an appropriate policy response to eutrophication is difficult. First, many economic activities contribute nutrients to the marine environment. These include agriculture; the disposal of household waste; population growth along rivers, estuaries, and on the coast; the conversion of wetlands; and the burning of fossil fuels. Thus, regulating the flow of nutrients could potentially touch on a large part of the economy. Second, the effects of eutrophication are complex and difficult to measure in economic terms. While certain parts of the problem have received attention by scientists and economists, there is no comprehensive assessment of the potential costs and benefits of alternative strategies to control marine eutrophication. Third, while coastal eutrophication is ubiquitous and increasing, every eutrophic zone is to some extent different in terms of both causes and effects, so that policies will have to be customized to local conditions

In this situation, it seems wise to begin by focusing on low cost options for controlling nutrients, especially those with benefits beyond the reduction of eutrophication; to encourage the development of local and regional approaches; and to support economic and scientific efforts to address key uncertainties and to evaluate the costs and benefits of different strategies. Experience suggests that, within any activity that contributes nutrients to coastal waters, some low-cost reduction is possible. The fact that there are so many such activities suggests, in turn, that there is considerable scope for low-cost reductions. In the case of agriculture, the loss of unutilized fertilizer to the environment itself constitutes an economic loss to producers, so that inexpensive measures to prevent this loss will have benefits beyond the marine environment. Fortunately, a number of relatively inexpensive measures are available to reduce fertilizer loss. These include the use of improved soil and crop testing, remote sensing, and other information to fine-tune fertilizer application over time and across fields and the use of no-till or conservation tillage to reduce erosion and consequent nutrient loss. Curtailing the conversion of wetlands and other buffers that intercept and sequester nutrients and restoring some of those that have already been lost are other promising options, as is upgrading septic facilities and sewage treatment. There is also a clear need for improved treatment of growing concentrations of animal waste. Although these options are more costly, they have benefits beyond reducing coastal eutrophication. For example, wetlands provide refuge for fish, birds, and other animals and thus contribute to the maintenance of biological diversity, while improved handling of sewage is an important priority in managing water quality generally. Finally, the benefits to marine environmental quality should be added to the list of other benefits of reducing atmospheric emissions of nitrogen.

within any activity that contributes nutrients to coastal waters, some low-cost reduction is possible. The fact that there are so many such activities suggests, in turn, that there is considerable scope for low-cost reductions.

As environmental problems go, coastal eutrophication is not particularly glamorous. While it may be difficult to justify costly measures to eliminate eutrophication, particularly in the short-term, low-cost options do exist to take a step in that direction. Not only would undertaking these options make economic sense today, but they would set us on a course to lighten the tread of society on natural systems.