CAUSES AND CONSEQUENCES OF NUTRIENT OVERENRICHMENT OF COASTAL WATERS

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INTRODUCTION

While developed societies made significant progress in reducing the discharge of many wastes—including industrial wastes, organic matter in sewage, sludge, contaminated sediments and other material dumped at sea, toxic compounds, and oil-into coastal waters, nutrient over-enrichment intensified and spread widely among the planet's coastal environments during the last half of the 20th century. This has often had devastating effects on the fisheries, biodiversity and services provided by these ecosystems. Eutrophication, as used here, is the enrichment of aquatic environments by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of water concerned[1]. These nutrients come not only from treated waste streams, but also from land runoff, particularly from agriculture, and the atmospheric deposition of byproducts of fossil fuel combustion. These so-called nonpoint sources grew dramatically and are particularly hard to control. Its pervasive extent, consequences, trends, and challenges qualify the eutrophication of coastal waters as a planetary emergency of the early 21st century.

This report provides an overview of the causes and consequences of coastal eutrophication, its global patterns and trends, sources of nutrients and efforts to control them, and efforts to restore degraded ecosystems.

CAUSES AND CONSEQUENCES

Effects of Overenrichment

Mineral nutrients are, of course, essential to life and to the productivity of coastal ecosystems. Because they receive the infusion of nitrogen, phosphorus, silicon, iron and other minerals both from land—via river discharges—and from the ocean-via upwelling of nutrient-rich, deep waters—coastal ecosystems are among the most productive on Earth and are valued for their rich fishery production.

The input of nutrients can, however, overwhelm the capacity and resilience of the

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ecosystem. Nutrients stimulate microbes, including phytoplankton, and macroscopic plants to grow. Biomass of planktonic organisms and macroalgae may accumulate and then decompose, consuming much of the oxygen available in the water column. This is especially the case where the water column is stratified, with saltier, cooler water near the bottom. Decaying organic matter accumulates in bottom waters below the density gradient, consuming oxygen, which is not replenished by mixing from the surface waters. The bottom waters become hypoxic (with dissolved oxygen levels below the requirements of metabolically active fish and invertebrates) or even anoxic (with essentially no dissolved oxygen). Hypoxia can result in mass mortality of benthic (bottom dwelling) species and tinder chronic stress can convert the seabed into a virtual biological desert devoid of animal life[2].

An increase in nutrient supply generally increases the production of phytoplankton, but has a selective effect, increasing certain rapidly growing species at the expense of others. Blooms of planktonic algae reduce water clarity, and thus light penetration, and, because of this selective effect, alter the quality as well as the quantity of food for secondary consumers. The nature of the phytoplankton response depends on the mix of nutrients available. Many coastal systems are receiving increasing supplies of nitrogen from human activities, while supply of silicon, which is required by diatoms, is declining because of trapping of this natural product of crustal erosion behind upstream dams[3]. Under eutrophication, the phytoplankton base of the food chain shifts, away from larger celled organisms toward flagellates and bacteria. Increased primary production coupled with qualitative changes in the producers have consequences throughout the food chain, leading to diminished success of fish larvae, for example, and increased production of jellyfish[4].

Sometimes, this also results in blooms of species of dinoflagellates and other organisms that produce toxins or have other harmful effects[4]. In recent decades there has been a worldwide explosion in the extent and frequency of these so-called harmful algal blooms, including those that produce paralytic, diarrhetic, neurotoxic, and amnesic shellfish poisoning in humans. Although eutrophication is thought to be a contributing factor in many of these cases, it is by no means responsible for all harmful algal blooms, some of which are occurring naturally and others may result from changes in climate and human introductions among other causes.

In shallow coastal waters with ample light penetration, eutrophication may cause proliferation of macroalgae growing on the seabed. These macroalgae smother benthic habitats, deplete dissolved oxygen when they decompose, and create nuisances when washed up on beaches. Nutrient enrichment can cause overgrowth or coral reefs by macroalgae, particularly where overfishing has reduced the populations of grazing animals[5,6]. Eutrophication has also resulted in extensive losses of seagrass meadows due to shading by increased phytoplankton biomass and overgrowth by epiphytic algae[7].

Consequences to Ecosystems and Society

The broader consequences of these effects of eutrophication-hypoxia, algal blooms, food chain shifts, and loss of seagrass and coral reef habitats - to the ecosystems and to human society are significant, but incompletely known. Eutrophic coastal ecosystems that are oxygen stressed and microbially dominated have reduced biodiversity and resilience in the face of other natural and anthropogenic perturbations[6,8]. The effects on living resources in coastal waters arc complex and not easy to quantify, even when the region affected is large and periodically affected by severe hypoxia[8]. To a certain degree eutrophication may increase fisheries production, particularly by pelagic species that feed on the increased supplies of plankton in the water column, but as hypoxia in bottom waters develops, supplies of benthic fish and shellfish are reduced[9]. However, many coastal ecosystems are also affected by overfishing, particularly of predaceous species that exercise top-down controls on the structure of ecosystems[6,10]. The interactive effects of eutrophication and harvesting can result in ecosystems prone to nonlinear response and collapse (Fig. 1). Dramatically altered coastal ecosystems, from decimated coral reefs of the Caribbean to the coastal regions of the Black Sea, may be the ultimate consequence.

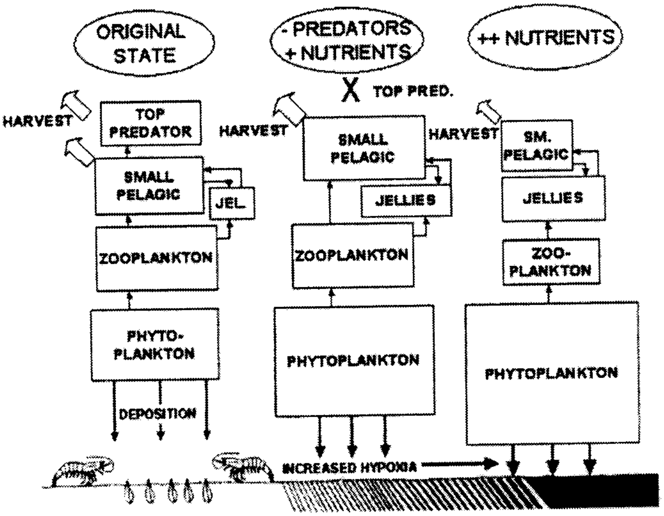

Figure 1. Simultaneous effects of eutrophication and fishery harvest on marine food chains (after Caddy[10]).

Species that are dependent on seagrass meadows or coral reefs are, of course, particularly susceptible to the loss or degradation of these habitats. In general, severe eutrophication is detrimental to the living resources of coastal ecosystems, however there remains considerable controversy about the degree to which eutrophication actually enhances production at higher trophic levels[11], whether the enrichment effects outweigh the detrimental effects[8], and about the consequences of reducing eutrophication on fisheries production[12]. In already productive coastal ecosystems, eutrophication tends to enhance the growth of forms of phytoplanklon that support microbial production rather than harvestable animal populations[13]. In addition to the effects on fisheries, eutrophication has other impacts on the economies of coastal communities, including diminished recreation and tourism[4]. For example, reduced water clarity, windrows of rotting algae on beaches, and health concerns about harmful algal blooms can deter beach goers and tourists, with devastating effects on local economies.

PATTERNS AND TRENDS

Worldwide Distribution

Many bays and estuaries and even some large regions of semi-enclosed seas exhibit the effects of severe eutrophication, including hypoxia, algal blooms, and loss of seagrasses. The problems are most severe in the Europe, North America and Japan, where there are large inputs of nutrients from land. Larger ecosystems affected include the Baltic Sea, the eastern North Sea, the northern Adriatic Sea, and the northwestern Black Sea in Europe; the Chesapeake Bay, northern Gulf of Mexico and Long Island Sound in the United States; the Seto Inland Sea in Japan; and the Gulf of Bohai-Yellow Sea in Asia (Fig. 2).

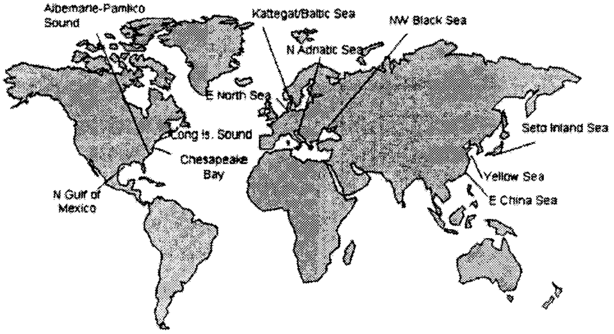

Figure 2. Semi-enclosed coastal seas experiencing severe eutrophication.

The deep basins of the Baltic Sea are continuously anoxia and many of the shallower embayments and the Kattegat at the entrance of the Baltic experience seasonal hypoxia[14,15]. Filamentous green algae have replaced brown seaweeds in shallow, rocky habitats and the depth at which attached algae can grow has diminished. Blooms of cyanobacteria and harmful algae occur with increased frequency and extent. The German Bight of the North Sea also experiences occasional hypoxia and extensive algal mats now cover the intertidal banks of the Wadden Sea as a result of the influx of North Sea water enriched by nutrients discharged from the 'mine and Elbe rivers'[6]. The northern Adriatic also undergoes seasonal hypoxia and produces noxious floating algal growth that fouls beaches[17]. Perhaps the most dramatic and extensive eutrophication was on the northwestern shelf of the Black Sea. Vast (10,000 km^2) meadows of attached red algae that once extended under clear water nearly disappeared as a result of decreased water clarity due to nutrient enrichment. Extensive hypoxia in bottom waters later developed, contributing, along with fishing pressure and introduced jellyfish, to the collapse of many fisheries

In North America, the most intensively studied coastal ecosystem infuenced by eutrophication is the Chesapeake Bay, a 300 km long estuary on the east coast. There seasonal hypoxia and anoxia in bottom waters have expanded and the majority of extensive seagrass beds that once covered many shallow water environments have been lost[19]. The deeper pans of Long Island Sound, east of New York City, experience seasonal hypoxia[20]. The continental shelf of the northern Gulf of Mexico off of the Mississippi River delta has the largest area of hypoxia, in some years covering 20,000 km2 of seabed[21]. Gulf of Mexico hypoxia has been the subject of a recent integrated assessment of its distribution, variability, causes, and history[22].

Several portions of the Seto Inland Sea in Japan witness seasonal hypoxia and harmful algal blooms as a result of eutrophication[23]. In addition, other large shallow embayments, including Tokyo Bay and Ise Bay experience severe hypoxia. Elsewhere in Asia, hypoxia has been observed off the mouth of the Chang Jiang (Yangtze) River and coastal waters in the Yellow Sea, particularly in the Gulf of Bohai, are experiencing increased frequency and severity of harmful algal blooms.

In addition to these larger coastal water bodies, ranging from large bays to the Baltic Sea, there are many smaller bays and estuaries in Europe, North America, Asia and Australia that are degraded by eutrophication. For example, 44 of 138 estuaries along the coast of the United States have high levels of eutrophication and an additional 40 have moderate symptoms[24]. These symptoms include increased phytoplankton growth, increased growth of macroalgae and epiphytes, low dissolved oxygen, harmful algal blooms, and loss of seagrass Similarly, eutrophication of coastal bays, fjords and lagoons is a widespread problem in Europe[25].

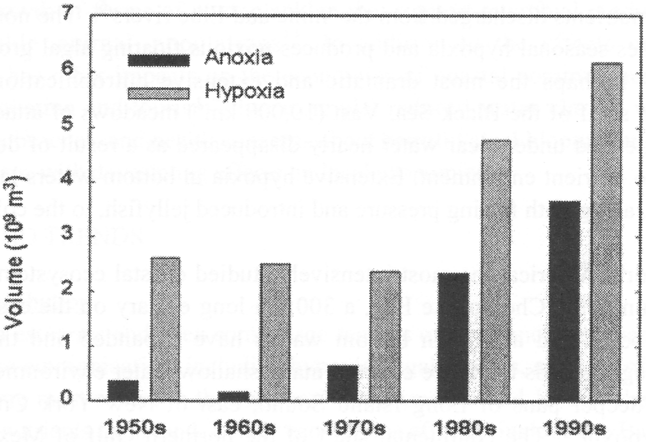

Figure 3. Changes in the volume of summertime hypoxic and anoxic water in Chesapeake Bay[27].

Late 20th Century Phenomenon

Although some coastal ecosystems, particularly those off the mouths of major rivers, are naturally eutrophic, there is strong and parallel evidence that coastal eutrophication greatly intensified during the latter half of the 20th century. This evidence is based both on direct periodic observations of nutrient levels, water clarity, dissolved oxygen levels, seagrass distribution, and algal blooms and historic reconstructions using the chemical constituents and microfossils of buried sediments. For example, increasing trends in nitrogen or phosphorus have been demonstrated for the Black Sea, Baltic Sea and Irish Sea after the 1950s[1]. In one of the few areas where it has been consistently measured, primary production by phytoplankton doubled from the beginning of the 1960s to the 1990s in the southern Kattegat between Denmark and Sweden[26]. Using the same simple technology, the Secchi disk, first used there early in the century light penetration was shown to have declined dramatically in the northern Adriatic Sea after the middle of the century. The volume of summertime hypoxic and anoxic water in the Chesapeake Bay progressively increased during the decades of the 1970s, 1980s and 1990s[27] (Fig. 3).

Water transparency declined, extent of hypoxia increased, and harmful algal blooms became more frequent in Mikawa Bay, Japan after the late 1950s and into the 1980s[28] (Fig. 4).

The sediment record in the central basin of the Chesapeake Bay reveals a chronology of eutrophication that began with extensive land clearing by European colonists in the late 18th century[9]. More nutrients ran off the land, resulting in increased primary productivity and a shift in the type of dominant diatoms. Seasonal hypoxia was intermittent and modest until the 20th century and intensified during the during the 1950-1980 time period, as reflected in the degree of pyritization of iron, levels of reducible sulfur, and assemblages of microfossils.

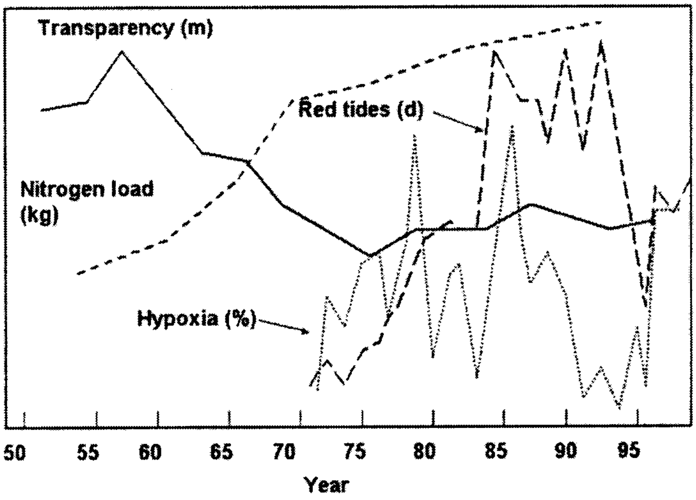

Figure 4. Relative changes in nitrogen loading, water transparency, extent of hypoxia, and frequency of red tides in Mikawa Bay, Japan (after Suzuki[28]). Scales of the variables are relative to their ranges: nitrogen to 14 x 10^6 kg, transparency to 6.3 m, frequency of red tides to 365 days, and hypoxia to 10 percent of area of bay with less than 30% hypoxia.

The dramatic eutrophication seen in many coastal waters around the world after the 1950s reflects substantial increases in the loading of nutrients, particularly nitrogen. Increased nutrient loading resulted from population growth, the collection and discharge of human wastes into surface waters, intensification of animal production, the combustion of fossil fuels (with the concomitant release of nitrogen oxides into the atmosphere), and, particularly, the widespread use of manufactured fertilizers after World War II. In addition, the capacity of river catchments to retain nutrients was reduced as a result of artificial agricultural drainage, the elimination of wetlands and riparian forests, and constriction of flood plains for flood protection and river training. As a result of the increased fixation of nitrogen and mobilization of phosphorus, the flux of these nutrients into coastal regions increased virtually exponentially. For example, it is estimated that the present flux of nitrogen into the North Sea is 13 times that when there was no human influence, flux along the northeastern United Sates nine times, and flux from the U.S. into the Gulf of Mexico five times[29]. The flux of nitrate, the principal form of inorganic nitrogen, from the Mississippi River basin into the Gulf of Mexico increased by a factor of three since the 196Os[30].

Sources of Nutrients

Fundamentally, the sources of human-mobilized phosphorus entering coastal ecosystems are soil erosion (as phosphorus tends to be bound to particles), agricultural fertilizers (largely mined from geological deposits), and industrial or domestic chemicals (e.g. detergents). These enter surface waters via diffuse sources of runoff from agriculture (from soil, fertilizers, and animal wastes) or urban and suburban areas and via point-source discharges of sewage or industrial wastes. Sewage and agricultural runoff typically dominate.

The fundamental anthropogenic sources of fixed nitrogen entering coastal waters are the combustion of fossil fuels (which release nitrogen oxides or NO_2 into the atmosphere), manufactured nitrogen fertilizers, biological fixation by crops, and mineralization of organic matter long sequestered in soils. Nitrogen has been called the most promiscuous element, because it can easily move from gaseous to dissolved to solid phases. Its many sources and routes make it more challenging to control than phosphorus. Atmospheric NO_2 can be deposited on land or surface waters dissolved in rain or in particulate form and is a significant cause of acid deposition as well as coastal eutrophication. Nitrogen may easily enter ground water (because of the high solubility of nitrate). Fertilizers are the original source of most of nitrogen in sewage discharges (from food), but because 70 percent of crops is fed to animals, much of the nitrogen in crops ends up in animal wastes, where some of it volatilizes as ammonia, to be deposited somewhere downwind. Because nitrogen typically limits primary productivity in marine as opposed to freshwater environments, most of the focus of abatement programs and the remaining discussion is on nitrogen.

The relative importance of anthropogenic nutrient sources varies greatly among affected coastal ecosystems. Using the U.S. Atlantic and Gulf coasts as an example (Fig. 4), the loadings of nitrogen into coastal waters with little agriculture in their catchments and receiving waste waters from urban centers, such as Massachusetts Bay (Boston) and Long Island Sound (New York City), are dominated by point source discharges[31]. Nitrogen loadings into coastal waters with heavily agricultural catchmcnts, such as the Louisiana continental shelf off the Mississippi River or Pamilco-Abemarle Sound in North Carolina are dominated by agricultural sources (runoff; groundwater nitrogen losses, and deposited ammonia). Some coastal ecosystems, such as the Chesapeake Bay, receive a mix of inputs from agriculture, atmospheric deposition of NO_2, and point source discharges of sewage from its population centers. This means that pollution abatement strategies often have to be multi-pronged. Agricultural sources contribute half or more of the nitrogen loading in the larger eutrophic coastal systems that receive the discharges from large catchments, including the Baltic, Adriatic and Black Seas, the northern Gulf of

Mexico and Chesapeake Bay.

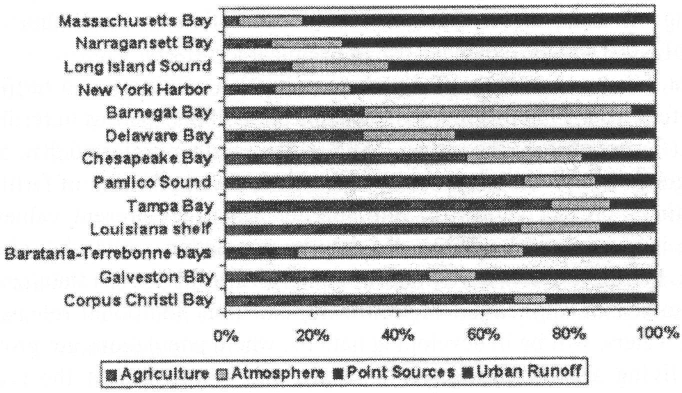

Figure 5. Proportion of sources of nitrogen loadings to selected bays and estuaries along the U.S. Atlantic and Gulf coasts[31].

Susceptible Coastal Ecosystems

Not all coastal waters are equally susceptible to nutrient over-enrichment. The most susceptible systems are those with limited tidal exchange and mixing, long retention time, vertically stratified water masses, and relatively low background concentrations of suspended sediments[4]. Highly turbid and tidally energetic systems like San Francisco Bay are not as susceptible to eutrophication as partially stratified systems with relatively little tidal resuspension of sediments such as the Chesapeake flay, even though their nutrient loading rates may be greater. Similarly, deep waters that lie close to the coast, such as off Southern California, provide rapid dilution of even large nutrient discharges without displaying eutrophication. This means that controlling nutrient inputs is of relatively little importance for achieving a healthy coastal environment in some areas, while it is of paramount importance in others.

THE FUTURE

Expanding Food Production and Energy Consumption

The widespread coastal eutrophication that developed during the later half of the 20th century is largely a manifestation of dramatic change in the nitrogen cycle of the biosphere, in which the world's supply of fixed nitrogen more than doubled in just a few decades[32]. This increase was much faster than the increase of CO_2 in the atmosphere and any other so-called global change. It has resulted in air quality problems (ozone formation), lake and soil acidification, reduced biodiversity in terrestrial ecosystems, and releases of N_2O (a potent greenhouse gas), as well as coastal eutrophication. The increase in nitrogen loading has been driven by increased consumption of fossil fuels (and associated release of NO_2) and the expanded use of chemical fertilizers.

Tilman et al.[33] demonstrated that the global application of nitrogen in fertilizers increased by eight-fold from 1960 to 1980 and the application of phosphorus in fertilizers grew by three-fold (figures exclude the former USSR). They further projected that, as the world population grows from 6 billion to 9 billion by 2050, the application of fertilizers will increase 2.7 times present values for nitrogen and 2.4 times present values for phosphorus. These increases will be driven not only by population growth but also by diets richer in meat. Fertilizer use in western Europe and North America has stabilized, so that most of this increased application of fertilizers, and thus additional releases of nutrients to coastal waters, will be in developing nations, where populations are growing and standards of living are increasing. As a result, one would expect the coastal eutrophication well in evidence in the developed world will expand to other coastal regions[34].

Controlling Sources of Nutrients

Significant reductions in nutrient inputs to coastal waters may be achieved by approaches that: (1) reduce the use of the nutrients in the first place; (2) control losses to the environment at the point of release (e.g. farm field, animal feeding operation, residential area, vehicle, power plant, or waste treatment plant); and (3) sequester or remove pollutants as they are transported to the sea[31,35].

A grand demonstration of the effectiveness of nutrient source reduction on eutrophication of coastal waters was presented in the northwestern Black Sea during the 1990s[36]. With the collapse of the centrally planned economics of eastern Europe, the applications of fertilizers rapidly declined to less than half the levels of the 1980s (Figure 6). Discharges of phosphorus and subsequently nitrogen declined several years later. In 1996 there was no hypoxic zone on the northwestern shelf of the North Sea for the first time in 23 years. Of course, the challenge we face is to reduce nutrient loadings from agricultural and other sources without having to suffer the economic collapse experienced in eastern Europe.

Phosphorus can be almost completely removed from wastewaters by additional chemical and biological treatment. This is now a widespread practice in Europe and North America and, along with bans of phosphate-based detergents, has resulted in significant reductions of phosphorus loading[25]. Significant nitrogen removal from wastewaters has been achieved in Scandinavia and for some U.S. estuaries by biological nutrient removal, a process in which one group of microorganisms convert wastewater ammonia to nitrate and another converts nitrate to dinitrogen gas[4].

Reductions in nitrogen oxide (NO_2) emissions to the atmosphere have been driven by air quality considerations generally outside the influence of water quality or coastal ecosystem managers. Goals have been to reduce ground-level ozone that poses human health risks and stresses forests and crops. Some reductions in emissions in NO_2 emissions from power plants and vehicles have been achieved in Europe and the U.S. and significant reductions should be achieved by additional regulations designed to meet air quality requirements.

Abatement of agricultural sources of nutrient pollution has been a more difficult challenge. To be practical, abatement of agricultural sources of nutrients must focus not only on reducing fertilizer use but also on plugging the many leaks in agricultural nutrient cycles. Although efficiencies in fertilizer use have been slowly but steadily increasing since the mid-197Os in western nations, about one-third of the nitrogen applied in the U.S. is not recovered in harvested crops[4]. Not all of the missing nitrogen contributes to eutrophication of coastal waters. Much is denitrified in soils or aquatic systems en route to the sea or is stored in soils or groundwater. In addition to increasing the efficiency of nitrogen uptake by crops, the return of nitrogen gas to the atmosphere can be enhanced through management practices.

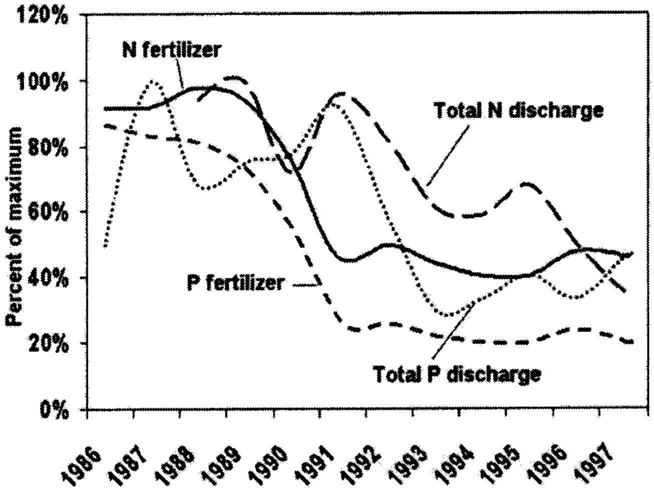

Figure. 6. Changes in the amount of nitrogen and phosphorus applied as fertilizers in the Danube River catchment and the loadings by the river to the Black Sea[36].

Various agricultural practices affect nitrogen and phosphorus runoff and losses to groundwater (which ultimately seeps into surface waters). Practices employed to reduce soil erosion also reduce nutrient pollution. Other practices are more specifically targeted to the efficient use and retention of nutrients: (1) soil testing to precisely match fertilizer applications to crop nutritional needs (many farmers still overapply to insure maximum crop yields); (2) applying fertilizer just at the time the crop needs it; (3) crop rotation; (4) planting cover crops in the fall; (5) using soil and manure amendments, and (6) specialized methods of application[4,31]. Landscape practices such as maintaining buffer strips between cultivated fields and nearby streams, moderating excessive drainage by ditches and tile lines, and maintaining wooded riparian areas can further reduce the leakage of agricultural nutrients to surface waters. By combining these approaches a significant portion of the edge-of-field nitrogen losses can be reduced.

Animal wastes are often the most significant source of nutrient pollution from agriculture[4,25]. Proper management of manures requires effective holding facilities and avoidance of overloading soils with manure applications. This is frequently difficult in regions of intensive animal production. Enclosures or trapping devices may eventually be required to stem ammonia emissions from animal wastes.

Urban runoff can also be an important diffuse source of nutrients. Reduction and control of urban and suburban diffuse sources can be achieved through: (1) reductions in horticultural fertilizer use; (2) effective and well-maintained stormwater collection systems (retention ponds can remove 30-40 percent of the total nitrogen and 50-60 percent of the total phosphorus); and (3) improved septic systems that promote denitrification[4]. Preservation and restoration of riparian zones and streams within urban and suburban areas is also an important aspect of effective nutrient control.

Removing or sequestering pollutants as they are transported downstream can also abate nutrient pollution. Often the majority of wetlands that once existed in a catchment have been drained and convened to other land uses. Also, floodplains have commonly been disconnected from their rivers by flood control projects or agricultural conversion and no longer serve as nutrient sinks. Because even the best land management practices will still release nutrients to surface or ground waters, reducing and controlling sources of land runoff must involve large-scale landscape management, including restoration of riparian zones and wetlands. For example, an integrated assessment of hypoxia in the Gulf of Mexico estimated that two million hectares of restored wetlands in the Mississippi River basin would reduce nitrogen loading to the Gulf of Mexico by 20 percent[22]. Coupled with feasible controls in agriculture, this would achieve a nearly 40 percent reduction in nitrogen delivered to the Gulf.

Coastal Seas Management

The various problems experienced by coastal ecosystems must be addressed by integrated approaches that address fishing activities and coastal zone development and related habitat modification, as well as pollution by nutrients and contaminants. But, to reduce the undesirable consequences of eutrophication such management must often reach beyond the coastal zone proper to extend to the entire catchment basin. Moreover, it may have to consider nitrogen originating outside of the catchment but transported into it through the atmosphere. These large and unconventional units for ocean and coastal resource management pose numerous challenges.

Concerted efforts to reverse nutrient over-enrichment are being undertaken for coastal ecosystems that range in size from small estuaries to the Baltic Sea. Once the seriousness and causes of coastal eutrophication began to be understood, multi-jurisdictional commitments were made in the late 1980s to reduce nutrient loadings of nitrogen and phosphorus to the Chesapeake Bay (by 40 percent of "controllable" loads), Baltic Sea (by 50 percent) and North Sea (by *50* percent). Multi-jurisdictional compacts-through the Chesapeake Bay Program, the Helsinki Commission, and the Paris Commission, respectively—established these commitments and guide and monitor their implementation[37]. Subsequent agreements were reached to stabilize the reduced loading levels to the Black Sea[36] and to reduce nitrogen loading from the Mississippi River basin by 30%. Other estuarine management plans[4], river basin action plans[25], or national laws (e.g. Denmark) have also established ambitious goals for reduction of nutrient loadings. These programs challenge intergovernmental commitments and actions. For example, for the Black Sea they must engage not only the six littoral nations, but also 11 other riparian nations in the catchment. Some 30 U.S. states fall within the Mississippi River basin.

Thus far, efforts to reduce coastal eutrophication have met with encouraging but limited success. Nutrient loadings from some European rivers have been reduced, particularly for phosphorus (as a result of discontinuing phosphate-based detergents and waste treatment), but reductions of nitrogen loadings from nonpoint sources have proven more difficult to achieve[25]. Improvements in coastal environmental quality have been achieved, for example in the Stockholm archipelago in the Baltic[15] and in Chesapeake Ray[19] and Tampa Bay[38] in the United States. Generally, these have come largely as a result of nitrogen and phosphorus removal from point sources. Greater success in reducing nonpoint sources, particularly from agriculture, will be required to achieve the restoration goals for most coastal ecosystems.

Strategies to reduce coastal eutrophication place a premium on environmental modeling, and monitoring[1,4] in an adaptive management framework[37]. Models are needed to track sources through the catchment, target abatement, and relate nutrient inputs to coastal ecosystem responses. Monitoring is critical in determining the effectiveness of abatement strategies, evaluating responses of the ecosystem, and placing these responses in the context of ecosystem variability.

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