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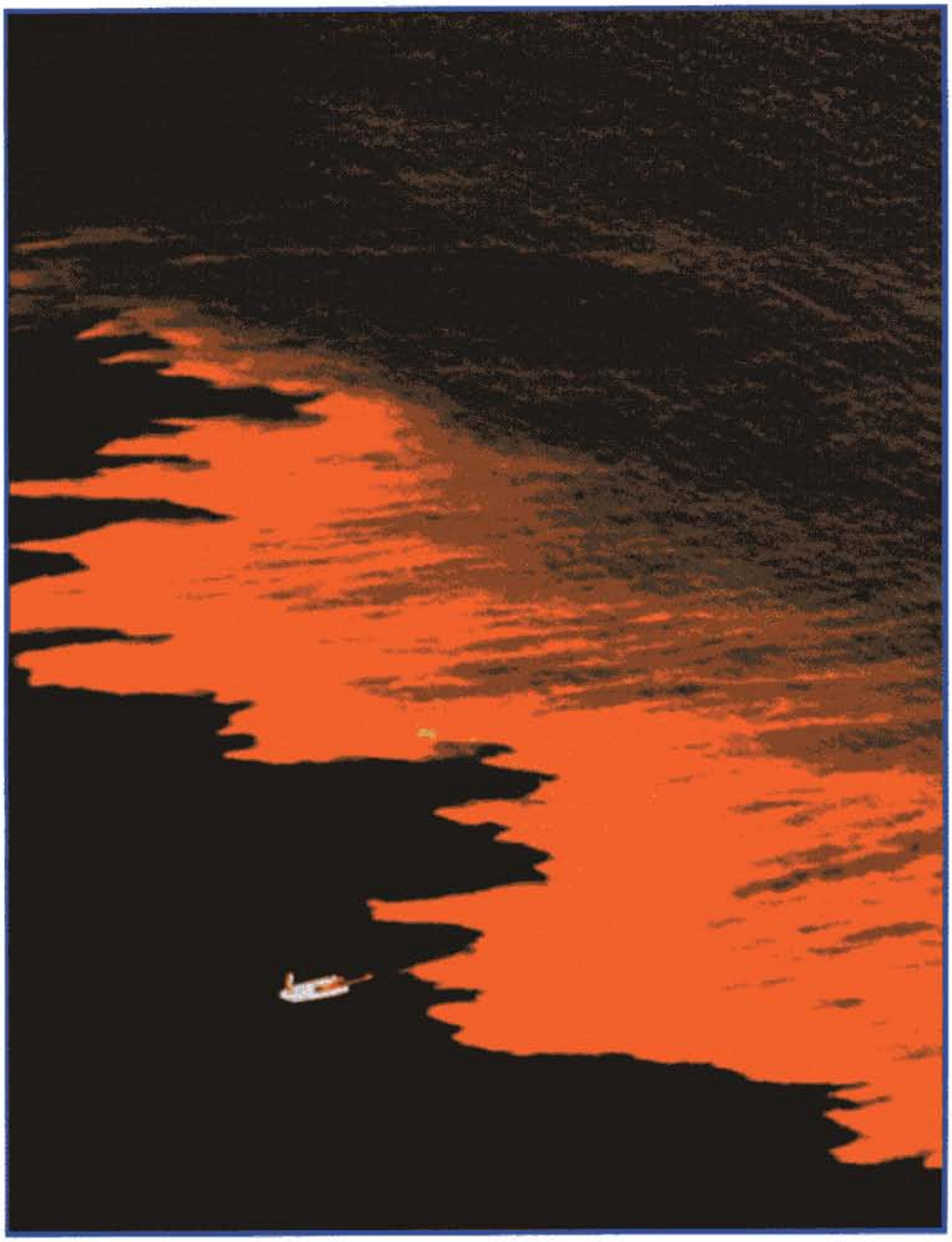
Nutrient Pollution of Coastal Rivers, Bays, and Seas



Nutrient Pollution of Coastal Rivers, Bays, and Seas

SUMMARY

Over the past 40 years, antipollution laws have greatly reduced discharges of toxic substances into our coastal waters. This effort, however, has focused largely on point-source pollution of industrial and municipal effluent. No comparable effort has been made to restrict the input of nitrogen (N) from municipal effluent, nor to control the flows of N and phosphorus (P) that enter waterways from dispersed or nonpoint sources such as agricultural and urban runoff or as airborne pollutants. As a result, inputs of nonpoint pollutants, particularly N, have increased dramatically. Nonpoint pollution from N and P now represents the largest pollution problem facing the vital coastal waters of the United States.

Nutrient pollution is the common thread that links an array of problems along the nation's coastline, including eutrophication, harmful algal blooms, "dead zones," fish kills, some shellfish poisonings, loss of seagrass and kelp beds, some coral reef destruction, and even some marine mammal and seabird deaths. More than 60 percent of our coastal rivers and bays in every coastal state of the continental United States are moderately to severely degraded by nutrient pollution. This degradation is particularly severe in the mid Atlantic states, in the southeast, and in the Gulf of Mexico.

A recent report from the National Research Council entitled "Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution" concludes that:

- Nutrient over-enrichment of coastal ecosystems generally triggers ecological changes that decrease the biological diversity of bays and estuaries.
- While moderate N enrichment of some coastal waters may increase fish production, over-enrichment generally degrades the marine food web that supports commercially valuable fish.
- The marked increase in nutrient pollution of coastal waters has been accompanied by an increase in harmful algal blooms, and in at least some cases, pollution has triggered these blooms.
- High nutrient levels and the changes they cause in water quality and the makeup of the algal community are detrimental to the health of coral reefs and the diversity of animal life supported by seagrass and kelp communities.
- Research during the past decade confirms that N is the chief culprit in eutrophication and other impacts of nutrient over-enrichment in temperate coastal waters, while P is most problematic in eutrophication of freshwater lakes.
- Human conversion of atmospheric N into biologically useable forms, principally synthetic inorganic fertilizers, now matches the natural rate of biological N fixation from all the land surfaces of the earth.
- Both agriculture and the burning of fossil fuels contribute significantly to nonpoint flows of N to coastal waters, either as direct runoff or airborne pollutants.
- N from animal wastes that leaks directly to surface waters or is volatilized to the atmosphere as ammonia may be the largest single source of N that moves from agricultural operations into coastal waters.

The National Research Council report recommended that, as a minimum goal, the nation should work to reverse nutrient pollution in 10 percent of its degraded coastal systems by 2010 and 25 percent of them by 2020. Also, action should be taken to assure that the 40 percent of coastal areas now ranked as healthy do not develop symptoms of nutrient pollution.

Meeting these goals will require an array of strategies and approaches tailored to specific regions and coastal ecosystems. There is an urgent need for development and testing of techniques that can reliably pinpoint the sources of N pollutants to an estuary. For some coastal systems, N removal during treatment of human sewage may be sufficient to reverse nutrient pollution. For most coastal systems, however, the solutions will be more complex and may involve controls on N compounds emitted during fossil fuel combustion as well as incentives to reduce over-fertilization of agricultural fields and nutrient pollution from animal wastes in livestock feedlot operations.

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Nutrient Pollution of Coastal Rivers, Bays, and Seas

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INTRODUCTION

Antipollution laws enacted and enforced over the past 40 years have increasingly restricted discharge of toxic substances into coastal waters of the United States. While this effort has greatly reduced point-source pollution of toxic materials, oxygen-consuming organic materials (BOD), and to some extent phosphorus (P) from industrial and municipal effluent pipes, no comparable attempt has been made to restrict the input of nitrogen (N) from municipal effluent, nor to control the flows of N and P that enter waterways from dispersed or nonpoint sources such as agricultural and urban runoff or windborne deposits. As a consequence, inputs of nonpoint pollutants, particularly N, have increased dramatically. Today, pollution from the nutrients N and P represents the largest source of degradation in coastal waters, which include some of the richest and most productive habitats in the oceans. Roughly half of the global fisheries catch occurs in or is dependent upon coastal waters of the world.

Nutrient pollution is also called nutrient over-enrichment because both N and P are vital to plant growth. A wide range of problems plaguing near-shore waters worldwide, from fish kills to some coral reef destruction, can be linked directly or indirectly to excessive nutrient inputs. In the United States, for example, more than 60 percent of coastal rivers and bays are moderately to severely degraded by nutrient pollution. Although such problems occur in all coastal states, the situation is particularly acute in the mid Atlantic states, southeast, and Gulf of Mexico (Figure 1).

While inputs of both N and P contribute to the degradation of coastal rivers, bays, and seas, recent research has confirmed that N is particularly damaging to these systems. This contrasts with findings from freshwater lakes, where P has been demonstrated to be more critical in regulating water quality. Because of public concern over readily apparent fouling in lakes and rivers, water quality regulations over the past 30 years have focused largely on P, leaving N inputs to aquatic systems severely under-regulated.

The National Academies' National Research Council (NRC) recently reviewed the causes and consequences of this neglected pollution problem in a report entitled "Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution." All of the authors of this article participated — as members, staff, or invited experts — in the work of the NRC Committee on Causes and Management of Coastal Eutrophication and contributed to the NRC report. This article is intended to bring the findings and recommendations made in that report to a broader audience of non-specialists.

This article summarizes the ecological damage caused by nutrient pollution in coastal systems, discusses why N is of particular concern in these systems, and outlines the sources of N inputs to the coast. By highlighting the problem of nutrient pollution in coastal rivers, bays, and seas, this article builds upon two earlier volumes in the *Issues in Ecology* series: "Human Alteration of the Global Nitrogen Cycle: Causes and Consequences" (1997) and "Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen" (1998).

ECOLOGICAL DAMAGE FROM NUTRIENT POLLUTION

Nutrient over-enrichment has a range of effects on coastal systems, but in general, it brings on ecological changes that decrease the biological diversity – the variety of living organisms — in the ecosystem.

Fertilizing lakes, rivers, or coastal waters with previously scarce nutrients such as N or P usually boosts the primary productivity of these systems – that is, the production of algae (phytoplankton) that forms the base of the aquatic food web (Figure 2). This excessive, nutrient-induced increase in the production of organic matter is called eutrophication, and eutrophication is linked to a number of problems in aquatic ecosystems. As the mass of algae in the water grows, the water may become murkier; and particularly as the algae die and decompose, periods of oxygen depletion (hypoxia and anoxia) occur more frequently. Even living algae can contribute to oxygen depletion due to their oxygen consumption at night. These changes in nutrients, light, and oxygen favor some species over others and cause shifts in the structure of phytoplankton, zooplankton, and bottom-dwelling (benthic) communities. For instance, blooms of harmful algae such as red and brown tide organisms become more frequent and extensive, sometimes resulting in human shellfish poisonings and even marine mammal deaths. Oxygen depletion can cause fish kills and create "dead zones." Just as important, subtle changes in the plankton community and other ecological factors may trigger reduced growth and recruitment of fish species and lowered fishery production. Coral reefs and submerged plant communities such as seagrass beds can be harmed by loss of light from reduced water clarity, or from nutrient-induced growths of nuisance seaweeds.

Some coastal ecosystems are more susceptible to nutrient over-enrichment than others because a host of additional factors can influence the extent of plant productivity. These factors include how much light is available, how extensively algae are grazed by zooplankton and benthic suspension feeders, and how often a bay or estuary is flushed and its nutrients diluted by open ocean water. Thus, a given increase in nutrient inputs to coastal rivers and bays will boost primary production more in some systems than others. Yet susceptibility to nutrient over-enrichment is not static and can shift in response to such factors as climate change.

In some ecosystems, moderate nutrient enrichment can occasionally lead to increased populations of economically valuable fishes. More severe nutrient enrichment of these same waters, however, leads to losses of catchable fish. And even in systems where fish abundance is increased by nutrient inputs, other valued attributes such as biological diversity may decline. Other coastal ecosystems are highly vulnerable to eutrophication so that even small increases in nutrient inputs can be quite damaging. Coral reefs and seagrass beds, for instance, are particularly susceptible to changed conditions.

The single largest coastal system affected by eutrophication in the United States is the so-called "dead zone" in the Gulf of Mexico, an extensive area of reduced oxygen levels. In the early 1990s, the zone covered an estimated 9,500 square kilometers of the gulf, extending out from the mouth of the Mississippi River. By the summer of 1999, this hypoxic area had doubled to 20,000 square kilometers, an area the size of Lake Ontario or New Jersey.

Other severely impacted coastal systems in the United States include Chesapeake Bay, Long Island Sound, and the Florida Keys. In Europe, the Baltic, North, Adriatic, and Black Seas have all experienced problems from nutrient over-enrichment, especially eutrophication. In the Black Sea, eutrophication was partially reversed during the early1990's as nutrient inputs decreased following the collapse of the Soviet Union and fertilizer use in Eastern Europe dropped sharply. This decrease was temporary, however, and both nutrient inputs and eutrophication in the Black Sea have reached an all time high.

Effects on Ecological Communities

Eutrophication leads to changes in the structure of ecological communities by at least two mechanisms: indirectly through oxygen depletion and directly by increased nutrient concentrations.

Hypoxia and anoxia can change the makeup of a community by killing off more sensitive or less mobile organisms, reducing suitable habitat for others, and changing interactions between predators and their prey. For instance, recurring periods of low oxygen tend to shift the dominance in the seafloor community away from large, long-lived species such as clams to smaller, opportunistic, and short-lived species such as polychaete worms that can colonize and complete their life cycles quickly between the periods of hypoxia. Zooplankton that normally graze on algae in surface waters during the night and migrate toward the bottom in the daytime to escape the fish that prey on them may be more vulnerable to predation if hypoxia in bottom waters forces them to remain near the surface. Also, planktonic organisms such as diatoms, dinoflagellates, and copepods that live in surface waters (pelagic species) yet spend some life stages resting on the bottom may be unable to resume development if bottom layers remain oxygen depleted.

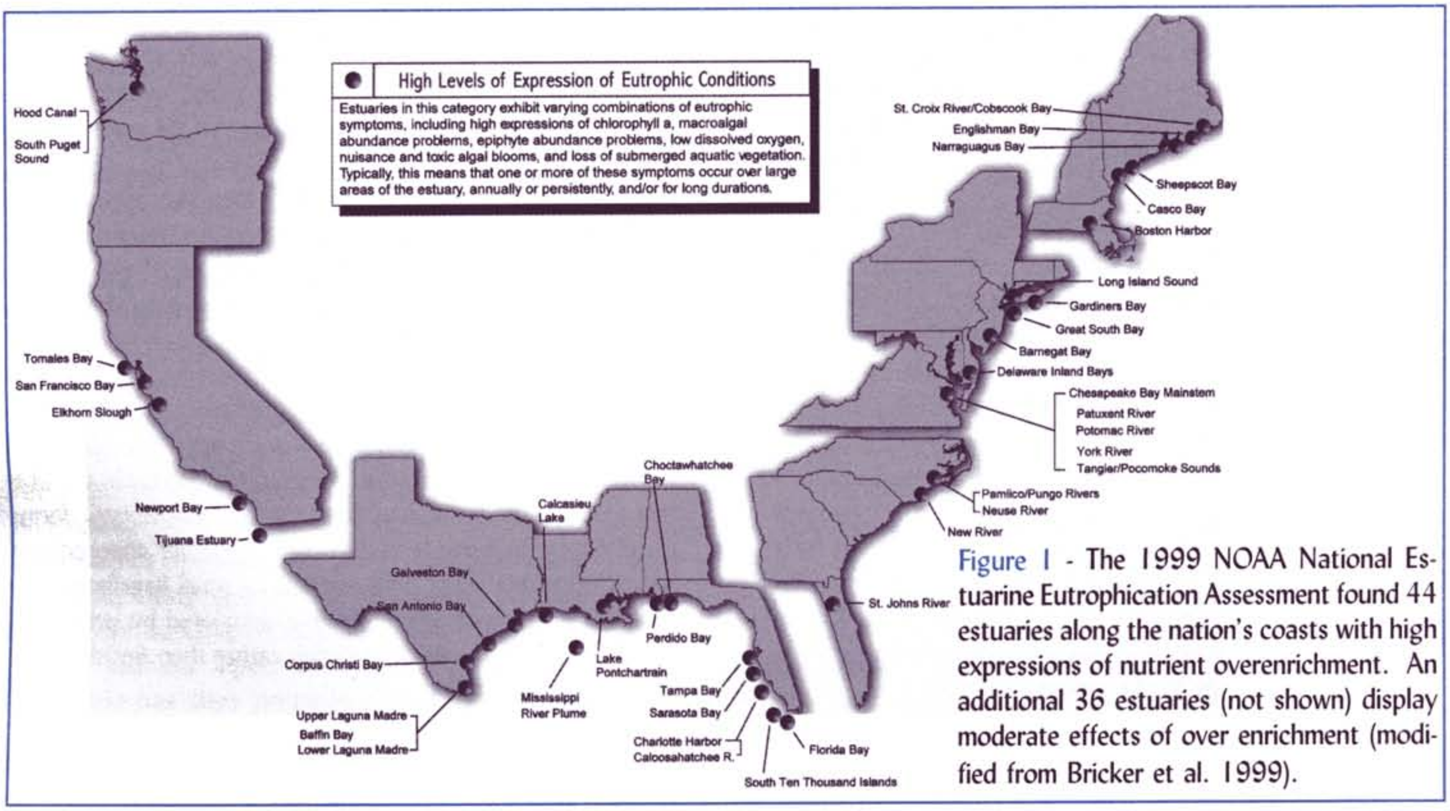
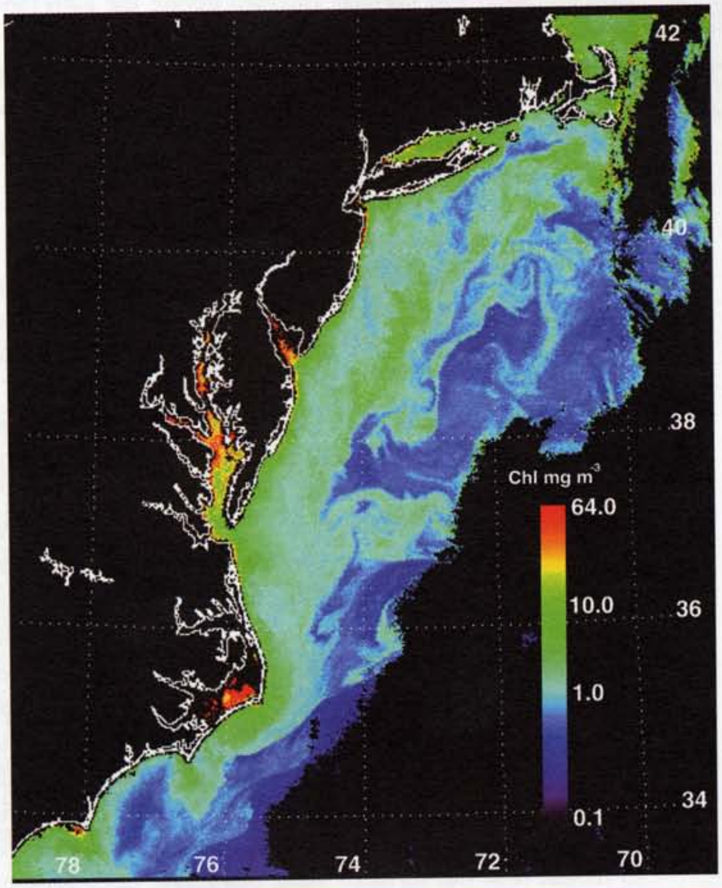


Figure 1 - The 1999 NOAA National Estuarine Eutrophication Assessment found 44 estuaries along the nation's coasts with high expressions of nutrient overenrichment. An additional 36 estuaries (not shown) display moderate effects of over enrichment (modified from Bricker et al. 1999).



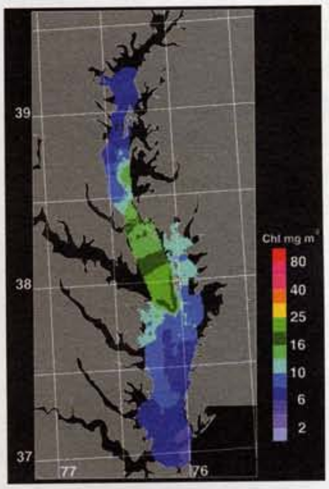


Figure 2 - The left panel shows the distribution of chlorophyll – an indicator of algal biomass – along the east coast of the U.S. from Boston to South Carolina as measured from the ocean color satellite SeaWIFs. Note the higher chlorophyll levels closer to shore, and the much higher levels in enclosed bays, such as Pamlico Sound (latitude 35°) and Chesapeake Bay (mouth at 37° latitude). The above panel shows chlorophyll distributions within Chesapeake Bay in more detail, as measured during a phytoplankton bloom. Both images were taken in April 1998.

Nutrient over-enrichment alters community structure directly by changing competition among algal species for nutrients. Algal species have wide differences in their requirements for and tolerances of nutrients and trace elements. Some species are well adapted to low-nutrient conditions while others prefer high levels of N and P. These differences allow a diverse phytoplankton community to maintain productivity in the face of broad shifts in nutrient supplies.

Eutrophication alters the phytoplankton community by decreasing availability of silica, which diatoms require to form their glasslike shells. Some silica that would otherwise be flushed into estuaries is used up in nutrient-induced diatom blooms upstream. As diatom production increases, silica is trapped long term in bottom sediments as diatoms die and sink. A decline in available silica can limit growth of diatoms or cause a shift from heavily silicified to less silicified types of diatoms. Studies off the German coast lasting more than two decades documented a general enrichment of coastal waters with N and P, along with a four-fold increase in ratios of available N and P to silica. This shift was accompanied by a striking change in the composition of the phytoplankton community, as diatoms decreased and flagellates increased more than ten-fold. Also, harmful blooms of colony-forming algae known as *Phaeocystis* became more common.

The availability of biologically useable forms of iron and other essential metals also can be affected by eutrophication, creating another factor that favors some algal species over others and alters the structure of the phytoplankton community. Because iron hydroxides have extremely low solubility, organic molecules must bind with iron if it is to remain in solution in seawater. Thus, dissolved organic matter (DOM) plays a critical role in enhancing biological availability of iron in coastal waters. A variety of factors can affect DOM levels in estuaries and coastal systems, but in general, eutrophication results in higher DOM levels and increases iron availability.

Because phytoplankton form the basis of the marine food chain, changes in the species composition of this community can have enormous consequences for animal grazers and predators. In general, these consequences are poorly studied, yet some outcomes are known. For instance, as noted above, eutrophication can lead to a change in dominance from diatoms towards flagellates, particularly if silica is depleted from the water. Such a change can potentially degrade the food webs that support commercially valuable fish species since most diatoms and other relative large forms of phytoplankton serve as food for the larger copepods on which larval fish feed. The presence of small flagellates may shift the grazer community to one dominated by gelatinous organisms such as salps or jellyfish rather than finfish.

Harmful Algal Blooms

Among the thousands of microscopic algae species in the phytoplankton community are a few dozen that produce powerful toxins or cause other harm to humans, fisheries resources, and coastal ecosystems (Figure 3). These species make their presence known in many ways, ranging from massive blooms of cells that discolor the water – so-called red or brown tides — to dilute, inconspicuous concentrations of cells noticed only because of damage caused by their potent toxins. Impacts can include mass mortalities of wild and farmed fish and shellfish, human poisonings from contaminated fish or shellfish, alterations of marine food webs through damage to larval or other life stages of commercial fisheries species, and death of marine mammals, seabirds, and other animals.

Although population explosions of toxic or noxious algal species are sometimes called red tides, they are more correctly called harmful algal blooms. As with most algal blooms, this proliferation and occasional dominance by particular species results from a combination of physical, chemical, and biological mechanisms and interactions that remain poorly understood. Although harmful algal blooms have occurred for at least thousands of years, there has been an increased incidence and duration of such outbreaks worldwide over the past several decades. This increase in harmful algal blooms has coincided with marked increases in nutrient inputs to coastal waters, and in at least some cases, nutrient pollution is to blame for the outbreaks.

A frequently cited example of the suspected link between harmful algal blooms and nutrient pollution involves the recently discovered "phantom" dinoflagellate *Pfiesteria*. In North Carolina estuaries and in the Chesapeake Bay, this organism has been linked to fish kills and to a variety of human health effects, including severe learning and memory problems. Because the organism and associated fish kills have occurred in watersheds that are heavily polluted by hog and chicken farm wastes and by municipal sewage, a strong case can be made that nutrient pollution serves as a major stimulant to outbreaks of *Pfiesteria* or *Pfiesteria*-like organisms. Nutrient-laden wastes could stimulate the outbreaks by either of two mechanisms. First, *Pfiesteria* is able to take up and use some of the dissolved organic nutrients in the waste directly. Second, this adaptable organism can consume algae that have grown more abundant because of the nutrient over-enrichment. Although the link between *Pfiesteria* outbreaks and nutrient pollution has not been fully proven, the evidence is sufficiently strong that legislation is already being developed and adopted to regulate waste handling at hog and chicken farms to reduce nutrient inputs to adjacent watersheds. *Pfiesteria* has thus prompted some agencies to address serious and long-standing pollution discharges by nonpoint sources that had previously avoided regulation.

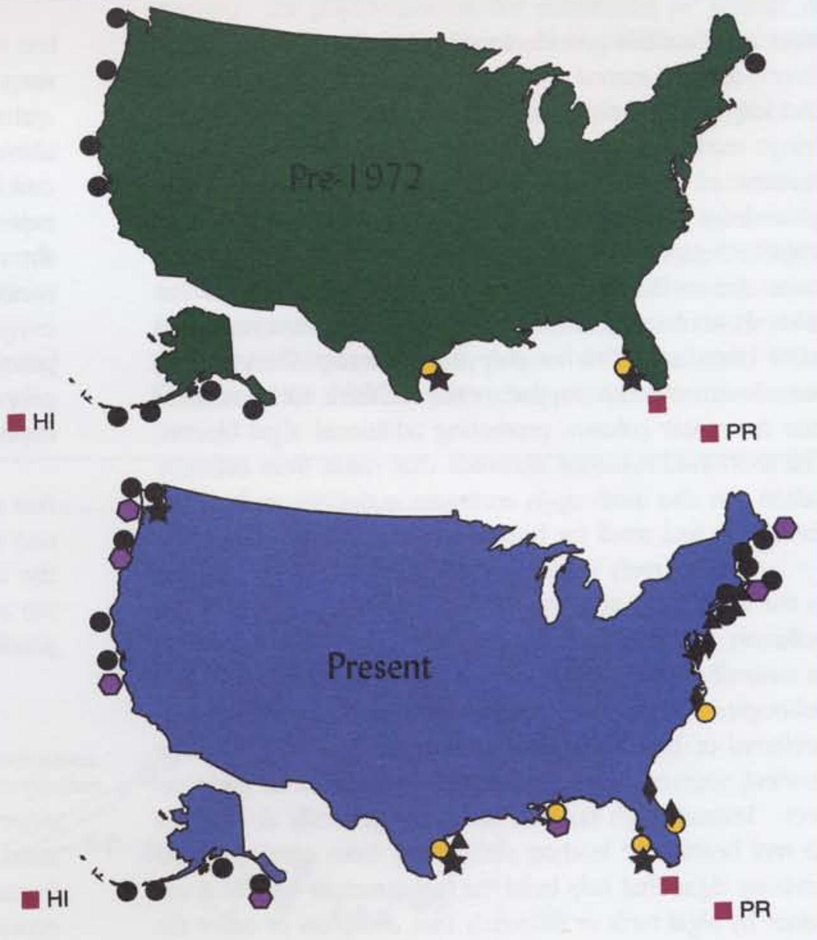


Figure 3 - This shows the expansion of harmful algal blooms in the United States pre-1972 to present. Ciguatera blooms accumulate toxins in fish, largely in tropical waters. Brown tides destroy shellfish beds. *Pfiesteria* kills fish and harms humans. (from Anderson 1995, as reprinted in NRC 2000).

Effects on Seagrass Beds and Corals

Eutrophication frequently leads to the degradation or complete loss of seagrass beds. Plant growth in these beds is often light limited, and eutrophication can lower light availability further by stimulating the growth of phytoplankton, epiphytes on the seagrass leaves, and nuisance blooms of ephemeral seaweeds (macroalgae) that shade out both seagrasses and perennial seaweeds such as kelp. In addition, eutrophication can lead to elevated concentrations of sulfide in the sediments of seagrass beds as algae and plant material decompose on the oxygen-depleted seafloor and seagrasses lose their ability to oxygenate the sediments. These elevated sulfide levels can slow the growth of seagrasses, which draw most of their nutrients from the sediments rather than the water column, or even poison them and lead to their decline.

Nutrient-induced changes generally lower the biological diversity of seagrass and kelp communities. Since these

Figure 4 - Nitrogen over-enrichment can lead to nuisance blooms of ephemeral seaweeds (macroalgae, left photo), which can have severe impacts on seagrass beds and coral reefs. On the right, sponges and corals overgrown by the seaweed *Codium isthmocladum* in Southeast Florida.

plant communities provide food and shelter for a rich and diverse array of marine animals, the degradation of seagrasses and kelp or their replacement by nuisance seaweed blooms brings marked changes in the associated animal life. These systems are particularly important as spawning and nursery grounds for fish. Further, the roots and rhizomes of seagrasses stabilize bottom sediments, and their dense leaf canopy promotes the settling out of fine particles from the water column. Loss of seagrass coverage, therefore, allows sediments to be stirred up. This not only reduces water clarity directly but allows nutrients trapped in the sediment to be released into the water column, promoting additional algal blooms. The short-lived nuisance seaweeds that result from eutrophication can also wash up in enormous quantities on beaches, creating a foul smell for beachgoers and coastal residents.

Coral reefs are among the most diverse ecosystems in the world, and also among the most sensitive to nutrient pollution. The world's major coral reef ecosystems are found in naturally nutrient-poor surface waters in the tropics and subtropics. It was once commonly thought that coral reefs preferred or thrived in areas of nutrient upwelling or other nutrient sources, but this idea has been shown to be incorrect. Instead, high nutrient levels are generally detrimental to reef health and lead to shifts away from corals and the coralline algae that help build the reef structure toward dominance by algal turfs or seaweeds that overgrow or cover the reefs. For example, some offshore reefs in the Florida Keys that contained more than 70 percent coral cover in the 1970s now have about 18 percent coral cover; mats of algal turf and seaweeds now dominate these reefs, accounting for 48 to 84 percent cover, and nutrient enrichment bears much of the blame (Figure 4). The effects of nutrient pollution, however, can often be exacerbated either by disease or overfishing, which reduce populations of sea urchins, fish, and other animals that graze on algae and help keep coral reefs clear.

Given the high light intensities and warm temperatures found in coral reef waters, the growth rates of ephemeral seaweeds are limited largely by the availability of essential nutrients. Thus even slight increases in dissolved nutrient concentrations can lead to expansion of these algae at the expense of coral. Increased seaweed cover on reefs inhibits the recruitment of corals and leads to a cascade of other ecological effects. For instance, seaweed blooms can lead to oxygen depletion on reef surface as these seaweeds decompose, and hypoxia in turn degrades habitat needed to support high diversity of coral reef organisms and potentially important grazers.

There is some evidence that N availability, in addition to temperature, light, and other environmental factors, may influence the "coral bleaching" phenomenon — loss of the algal partners known as zooxanthellae that live inside the cells of coral animals and nourish them — that has expanded globally in recent years.

WHICH NUTRIENTS MATTER?

The major nutrients that cause eutrophication and other adverse impacts associated with nutrient over-enrichment are N and P. Nitrogen is of paramount importance both in causing and controlling eutrophication in coastal marine ecosystems. This is in contrast to freshwater (or non-saline) lakes, where eutrophication is largely the result of excess P inputs. Other elements – particularly silica – may also play a role in regulating algal blooms in coastal waters and in determining some of the consequences of eutrophication.

Extensive studies in the early 1970s led to consensus that P was the nutrient most responsible for over-enrichment in freshwater lakes. Since that time, tighter restrictions on P inputs have greatly reduced eutrophication problems in these waters. However, more recent research indicates that in numerous estuaries and coastal marine ecosystems — at least in the temperate zone — N is generally more limiting to phytoplankton growth than P, and N inputs are more likely to accelerate eutrophication. A "limiting" nutrient is the essential plant nutrient in shortest supply relative to the needs of algae and plants, and adding it increases the rate of primary production.

There are exceptions to the generalization that N is limiting in coastal ecosystems. For instance, certain temperate estuaries such as the Apalachicola on the Gulf coast of Florida and several estuaries on the North Sea coast of the Netherlands appear to be P limited. In the case of the North Sea estuaries, P limitation most likely results from stringent controls the Dutch government has imposed on P releases, combined with high and largely unregulated human N inputs. In contrast, the high ratio of N to P in nutrient inflows to the Apalachicola may reflect the relatively small amount of human disturbance in the watershed and relatively low nutrient inputs overall.

In tropical coastal systems with carbonate sands and little human activity, P is generally limiting to primary production because the sand readily adsorbs phosphate, trapping it in the sediment and leaving it largely unavailable to organisms. However, such lagoons may move toward N limitation as they become eutrophic. The primary reason is that as more nutrients enter these waters, the rate at which sediments adsorb phosphate slows and a greater proportion of the P remains biologically available.

Even nutrient-poor tropical seas may be N limited away from shore, although the reasons are poorly understood. For example, much of the Caribbean Sea away from the immediate shorelines appears to be N limited.

The identity of the nutrient that limits plant production switches seasonally between N and P in some major estuaries such as Chesapeake Bay and portions of the Gulf of Mexico, including the "dead zone." Runoff in these systems is highest in the spring, and at that time the N:P ratio of the runoff determines which nutrient is limiting. In the summer, when runoff drops sharply, however, processes that occur in the sediment such as P adsorption and the bacterial breakdown of N compounds (denitrification) play a more important role in determining which nutrient is in shortest supply.

Even in these systems, N is probably responsible for the major harmful impacts of eutrophication. When waters are N limited, the algal community is dominated by diatoms, which tend to sink to the bottom, spurring decomposition processes that use up dissolved oxygen and create hypoxia. In contrast, when primary production is P limited in these systems, the phytoplankton are dominated by smaller or lighter algal species and relatively little sinks to the bottom.

Evidence for Control of Coastal Eutrophication by Nitrogen

Both researchers and policymakers have been slower to accept the need for tighter restrictions on N inputs than to acknowledge the need for P control to manage eutrophication in freshwater systems. Many coastal marine scientists recognized the N problem decades ago, yet the need for controls on N inputs was hotly debated throughout the 1980s. Only since the 1990s, when results from large-scale enrich-

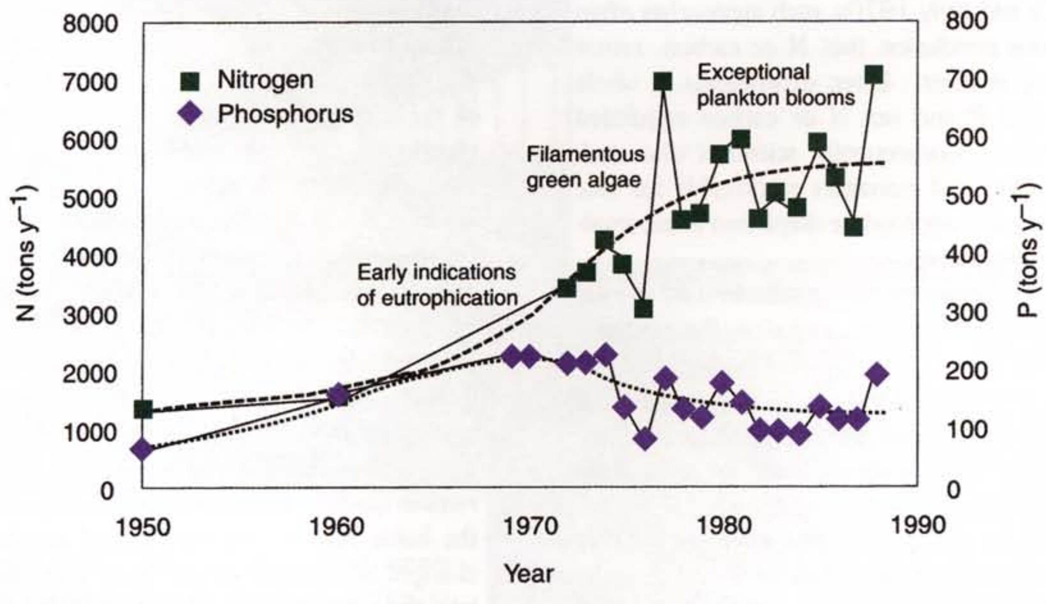


Figure 5 - The chart shows inputs of nitrogen and phosphorus to Laholm Bay on the coast of Sweden from 1950 to 1988. Note that P inputs decreased after 1970 due to control efforts, while inputs of N increased. Eutrophication first became apparent in the bay in 1970 and became much worse in the subsequent two decades, clearly indicating that N caused the eutrophication (modified from Rosenberg et al. 1990, as printed in NRC 2000).

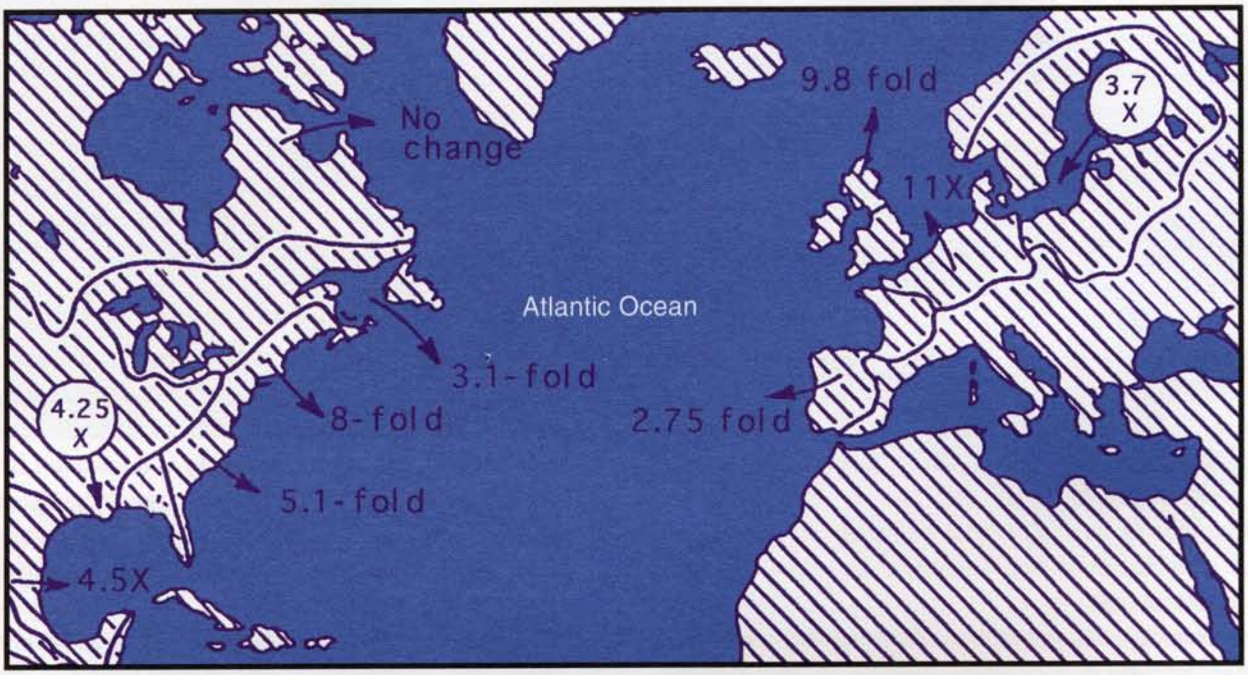


Figure 6 - Human activity has greatly increased the flux of nitrogen to coastal waters in many areas. (Based on data in Howarth, 1998.)

ment studies in three estuaries were published, has the need for controls on N been widely accepted.

Most early studies of nutrient limitation in coastal waters either relied on short-term and small-scale enrichment experiments to infer limitation by N or made inferences from laboratory studies. These approaches had fallen into disrepute because, when applied to the problem of lake eutrophication in the 1960s and early 1970s, such approaches often led to the erroneous conclusion that N or carbon, rather than P, was limiting in lakes. Later, experiments in whole lakes clearly showed P and not N or carbon regulated eutrophication in lakes. Consequently, scientists who studied lake eutrophication and managers responsible for lake water quality developed an appropriate skepticism about small-scale or lab-based approaches.

Other types of evidence have also been used to infer N limitation in coastal ecosystems, including the relatively low ratios of dissolved inorganic N to P found in many of these waters. Yet this type of bioassay result can also be criticized because concentrations of dissolved inorganic nutrients do not always accurately reflect the amounts available for uptake by living organisms.

In lakes, it took ecosystem-scale experiments to confirm eutrophication can be managed most successfully by controlling P inputs. A decade ago, there were no comparable experiments testing the relative importance of N and P in regulating eutrophication in coastal marine ecosystems. However, since 1990 the results of three such studies have shown these systems are N limited.

One of these experiments, a so-called mesocosm experiment conducted at the Marine Ecosystem Research Laboratory (MERL) on the shores of Narragansett Bay in Rhode Island, was specifically designed to see if coastal systems respond to nutrient additions in the same manner as lakes. A series of fiberglass tanks (mesocosms) more than 15 feet tall and six feet in diameter containing water and intact sediments from Narragansett Bay were maintained for a period of four months. Many previous studies in these mesocosms had demonstrated that these systems accurately mimic much of the ecological functioning of Narragansett Bay. In this experiment, each tank received a specific treatment: no nutrient enrichment, N alone, P alone, or both N and P. The levels of N and P enrichment paralleled levels used in an earlier whole-lake experiment in which the P inputs clearly led to eutrophication while N had no effect. In sharp contrast, the addition of the same level of N to the MERL coastal mesocosms -- either alone or with P, but not P alone — caused large increases in both rates of algal production and abundance of phytoplankton.

A second whole-ecosystem study took place in Himmerfjarden, an estuary south of Stockholm, Sweden, on the Baltic Sea. Researchers traced impacts of experimental changes in nutrient releases from a sewage treatment plant into the estuary from 1976 to 1993. For the first seven years, N loads gradually increased while P loads gradually decreased. For a one-year period beginning in the fall of 1983, P additions were greatly increased by halting removal of P during sewage treatment. In 1985, P removal was resumed while N inputs jumped 40 percent as a result of an increase in population served by the sewage treatment plant. Finally, N removal technology was gradually introduced to the sewage treatment plant between 1988 and 1993, eventually reducing the N load to the value originally seen in 1976. Throughout the 17 years of observation, both the clarity of the water and the abundance of phytoplankton were clearly related to the total N concentration in the estuary. In contrast, total P was a poor predictor of phytoplankton abundances.

A third study explored long-term changes in Laholm Bay, an estuary on the southwestern coast of Sweden (Figure 5). Early signs of eutrophication appeared there in the 1950s and 1960s and steadily increased over time. The earliest reported indicator of eutrophication was a change in the seaweed community, and filamentous or sheet-like seaweed species typical of eutrophic conditions have gradually become more prevalent. Harmful algal blooms also increased in frequency, particularly in the 1980s. During the early stages of eutrophication in Laholm Bay, inputs of both P and N were increasing. From the late 1960s through the 1980s, however, P inputs declined by a factor of almost two, while N inputs more than doubled. Plankton blooms continued and eutrophication worsened during this period, clearly indicating that N was controlling eutrophication in the bay.

Although these three large-scale studies show only that N controls eutrophication in Narragansett Bay, Himmerfjarden, and Laholm Bay, the findings are consistent with conclusions drawn from short-term bioassay studies and from ratios of dissolved inorganic N to P in these ecosystems. As a result, these three ecosystem studies add credence to results obtained from earlier studies. Most bioassay data from estuaries and coastal marine systems indicates that these are N limited. This is supported by the generally low inorganic N to P ratio found in most estuaries when they are at the peak of primary production. Thus, taken together, this body of evidence leads to the conclusion that N availability is the primary regulator of eutrophication in most coastal systems.

Mechanisms That Lead to Nitrogen Control of Eutrophication in Estuaries

Whether primary production by phytoplankton is limited by N or P depends on the relative availability of each of these nutrients in the water. Algal growth will slow when the concentration of the scarcest nutrient drops. Phytoplankton require approximately 16 moles of N for every mole of P they take in. This N:P ratio of 16:1 is called the Redfield ratio. If the ratio of available N to available P in an aquatic ecosystem is less than 16:1, algal growth will tend to be N limited. If the ratio is higher, primary production will tend to be P limited.

The relative availability of N and P to the phytoplankton is determined by three factors:

- the ratio of N to P that comes into the ecosystem from both natural and human-derived sources;
- how each nutrient is handled — stored, recycled, or lost — in the ecosystem;
- and how much N is "fixed" — converted from gaseous N in the air directly into biologically useable forms — within the ecosystem.

Photo by Larry Rana, USDA.

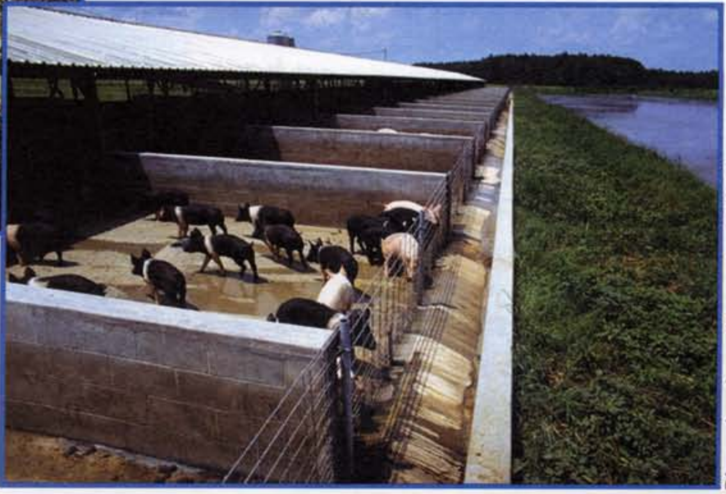


Photo by Gene Alexander, USDA.

Figure 7 - Animal wastes may be the largest single source of N that moves from agricultural production to coastal waters, either directly through runoff or indirectly through volatilization and deposition of atmospheric nitrogen.

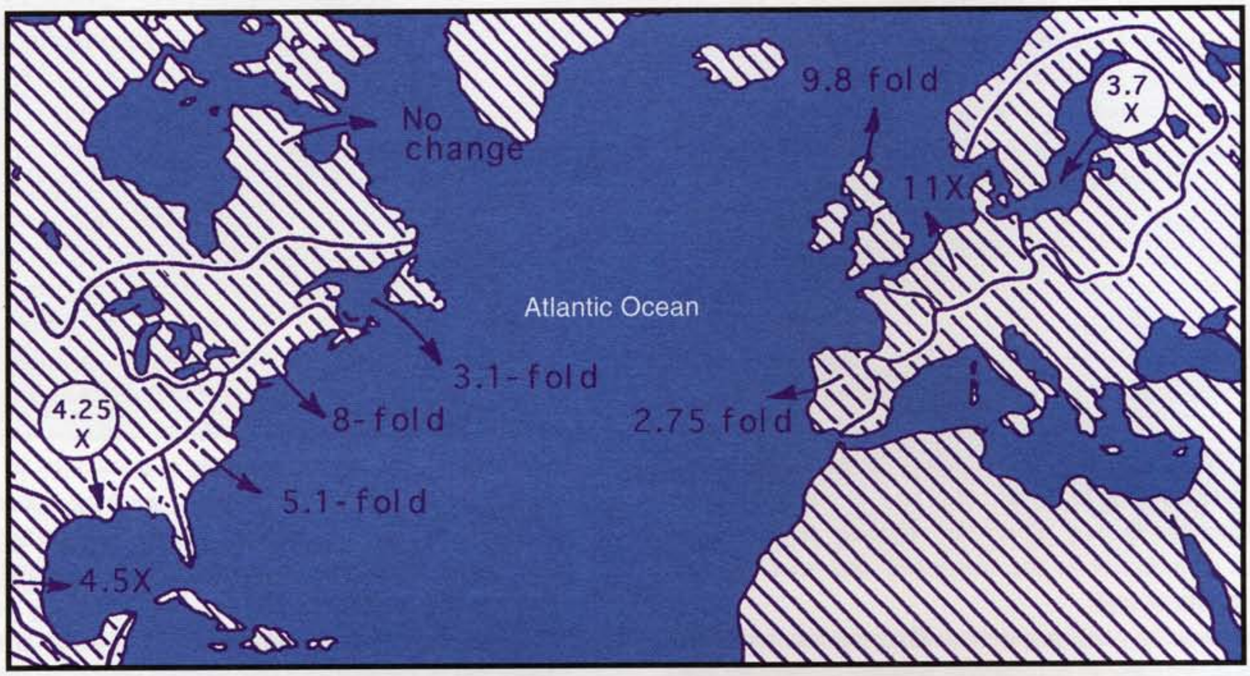


Figure 6 - Human activity has greatly increased the flux of nitrogen to coastal waters in many areas. (Based on data in Howarth, 1998.)

ment studies in three estuaries were published, has the need for controls on N been widely accepted.

Most early studies of nutrient limitation in coastal waters either relied on short-term and small-scale enrichment experiments to infer limitation by N or made inferences from laboratory studies. These approaches had fallen into disrepute because, when applied to the problem of lake eutrophication in the 1960s and early 1970s, such approaches often led to the erroneous conclusion that N or carbon, rather than P, was limiting in lakes. Later, experiments in whole lakes clearly showed P and not N or carbon regulated eutrophication in lakes. Consequently, scientists who studied lake eutrophication and managers responsible for lake water quality developed an appropriate skepticism about small-scale or lab-based approaches.

Other types of evidence have also been used to infer N limitation in coastal ecosystems, including the relatively low ratios of dissolved inorganic N to P found in many of these waters. Yet this type of bioassay result can also be criticized because concentrations of dissolved inorganic nutrients do not always accurately reflect the amounts available for uptake by living organisms.

In lakes, it took ecosystem-scale experiments to confirm eutrophication can be managed most successfully by controlling P inputs. A decade ago, there were no comparable experiments testing the relative importance of N and P in regulating eutrophication in coastal marine ecosystems. However, since 1990 the results of three such studies have shown these systems are N limited.

One of these experiments, a so-called mesocosm experiment conducted at the Marine Ecosystem Research Laboratory (MERL) on the shores of Narragansett Bay in Rhode Island, was specifically designed to see if coastal systems respond to nutrient additions in the same manner as lakes. A series of fiberglass tanks (mesocosms) more than 15 feet tall and six feet in diameter containing water and intact sediments from Narragansett Bay were maintained for a period of four months. Many previous studies in these mesocosms had demonstrated that these systems accurately mimic much of the ecological functioning of Narragansett Bay. In this experiment, each tank received a specific treatment: no nutrient enrichment, N alone, P alone, or both N and P. The levels of N and P enrichment paralleled levels used in an earlier whole-lake experiment in which the P inputs clearly led to eutrophication while N had no effect. In sharp contrast, the addition of the same level of N to the MERL coastal mesocosms -- either alone or with P, but not P alone — caused large increases in both rates of algal production and abundance of phytoplankton.

A second whole-ecosystem study took place in Himmerfjarden, an estuary south of Stockholm, Sweden, on the Baltic Sea. Researchers traced impacts of experimental changes in nutrient releases from a sewage treatment plant into the estuary from 1976 to 1993. For the first seven years, N loads gradually increased while P loads gradually decreased. For a one-year period beginning in the fall of 1983, P additions were greatly increased by halting removal of P during sewage treatment. In 1985, P removal was resumed while N inputs jumped 40 percent as a result of an increase in population served by the sewage treatment plant. Finally, N removal technology was gradually introduced to the sewage treatment plant between 1988 and 1993, eventually reducing the N load to the value originally seen in 1976. Throughout the 17 years of observation, both the clarity of the water and the abundance of phytoplankton were clearly related to the total N concentration in the estuary. In contrast, total P was a poor predictor of phytoplankton abundances.

A third study explored long-term changes in Laholm Bay, an estuary on the southwestern coast of Sweden (Figure 5). Early signs of eutrophication appeared there in the 1950s and 1960s and steadily increased over time. The earliest reported indicator of eutrophication was a change in the seaweed community, and filamentous or sheet-like seaweed species typical of eutrophic conditions have gradually become more prevalent. Harmful algal blooms also increased in frequency, particularly in the 1980s. During the early stages of eutrophication in Laholm Bay, inputs of both P and N were increasing. From the late 1960s through the 1980s, however, P inputs declined by a factor of almost two, while N inputs more than doubled. Plankton blooms continued and eutrophication worsened during this period, clearly indicating that N was controlling eutrophication in the bay.

Although these three large-scale studies show only that N controls eutrophication in Narragansett Bay, Himmerfjarden, and Laholm Bay, the findings are consistent with conclusions drawn from short-term bioassay studies and from ratios of dissolved inorganic N to P in these ecosystems. As a result, these three ecosystem studies add credence to results obtained from earlier studies. Most bioassay data from estuaries and coastal marine systems indicates that these are N limited. This is supported by the generally low inorganic N to P ratio found in most estuaries when they are at the peak of primary production. Thus, taken together, this body of evidence leads to the conclusion that N availability is the primary regulator of eutrophication in most coastal systems.

Mechanisms That Lead to Nitrogen Control of Eutrophication in Estuaries

Whether primary production by phytoplankton is limited by N or P depends on the relative availability of each of these nutrients in the water. Algal growth will slow when the concentration of the scarcest nutrient drops. Phytoplankton require approximately 16 moles of N for every mole of P they take in. This N:P ratio of 16:1 is called the Redfield ratio. If the ratio of available N to available P in an aquatic ecosystem is less than 16:1, algal growth will tend to be N limited. If the ratio is higher, primary production will tend to be P limited.

The relative availability of N and P to the phytoplankton is determined by three factors:

- the ratio of N to P that comes into the ecosystem from both natural and human-derived sources;
- how each nutrient is handled — stored, recycled, or lost — in the ecosystem;
- and how much N is "fixed" — converted from gaseous N in the air directly into biologically useable forms — within the ecosystem.

Photo by Larry Rana, USDA.

Photo by Gene Alexander, USDA.

Figure 7 - Animal wastes may be the largest single source of N that moves from agricultural production to coastal waters, either directly through runoff or indirectly through volatilization and deposition of atmospheric nitrogen.

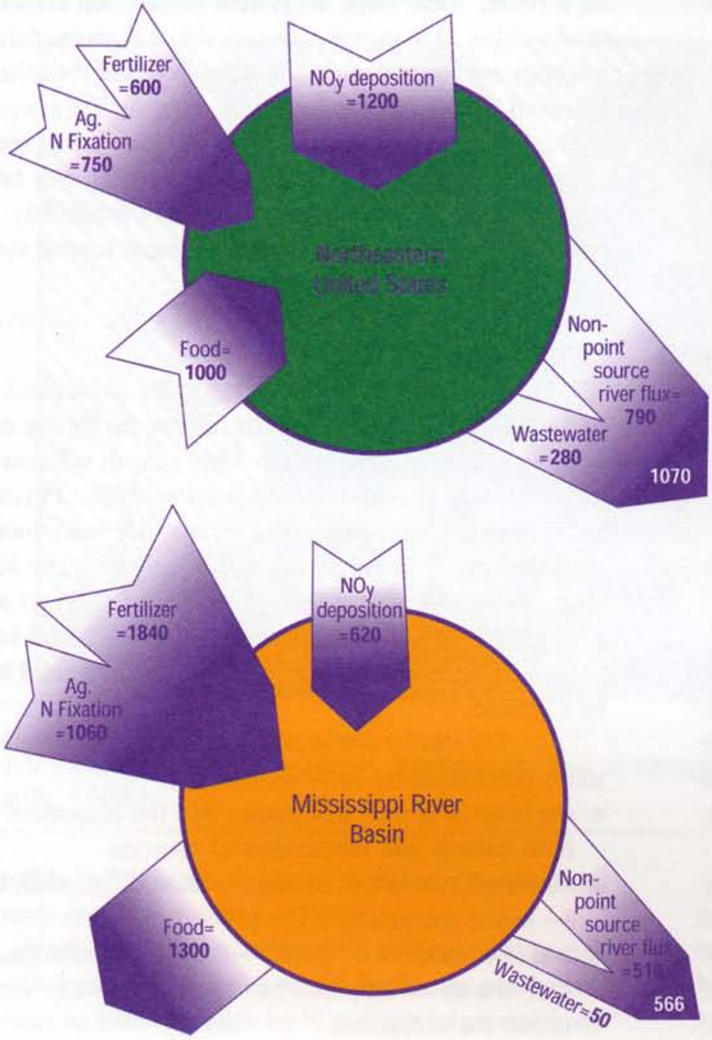


Figure 8 - On average, nitrogen is exported from the Mississippi River basin and imported to the northeastern US in the form of food crops. The flux of N down rivers to the coast is greater per area of watershed in the northeastern US than in the Mississippi basin. In the Northeast, atmospheric deposition from fossil fuel combustion, food imports, and fertilizer all contribute to these N exports to coastal waters. In the Mississippi basin, fertilizer and N fixation by agricultural crops contribute most to the flow of N into the Gulf of Mexico. (reprinted from NRC 2000).

These three factors interact in several ways to make N limitation more likely in estuaries and P limitation more likely in lakes. For instance, lakes receive nutrient inputs from upstream watersheds and from the atmosphere, while estuaries and coastal waters receive nutrients from these sources and neighboring ocean waters.

The ocean-water sources of nutrients for estuaries such as those along the northeastern coast of the United States tend to have an N:P ratio well below the Redfield ratio thanks to the activity of denitrifying bacteria on the continental shelf. These bacteria break down nitrate to obtain oxygen, a process that releases N to the atmosphere. Thus, given similar nutrient inputs from land, estuaries are more likely to be N limited than are lakes.

Freshwater lakes and coastal marine ecosystems also differ in their level of nitrogen fixation, and these differences are a major reason why so many estuaries are N limited while lakes are P limited. If a lake of moderate productivity begins to experience a shortage of N, blooms of nitrogen-fixing cyanobacteria (formerly called blue-green algae) occur, and the cyanobacteria tend to fix enough N to alleviate the shortage. Primary productivity of the lake remains limited by available P. This has been demonstrated in whole-lake experiments by fertilizing a lake with a constant amount of P over several years. For the first few years, the lake also received relatively high levels of N fertilizer so that the ratio of N:P was above the Redfield ratio. Under these conditions, no nitrogen fixation occurred in the lake. The experimental treatment was then altered so that the lake received the same amount of P, but a reduced amount of N so that the input was below the Redfield ratio. Nitrogen-fixing organisms quickly appeared and made up the N deficit.

Estuaries and eutrophic coastal waters provide a striking contrast with this behavior. With only a few exceptions anywhere in the world, nitrogen fixation by planktonic cyanobacteria is immeasurably low in these waters, even when they are quite N limited, and this allows N shortages to persist. There is a growing consensus that nitrogen fixation in marine systems – estuaries, coastal seas, as well as oceanic waters – probably is regulated by complex interactions of chemical, biological, and physical factors. Recent evidence indicates that cyanobacteria in coastal bays and rivers, for instance, are constrained by slow growth rates caused by shortages of trace metals such as iron or molybdenum and by grazing by zooplankton and bottom-dwelling animals.

Other elements besides N and P also can have a major influence on the structure of aquatic communities and can affect the nature of their response to eutrophication. As noted above, a key element in this regard is silica, an element required by diatoms. The availability of silica has little or no influence on the overall rate of algal growth in an aquatic system, but when silica is abundant, diatoms are one of the major components of the phytoplankton. When silica is in low supply, other classes of algae dominate the phytoplankton community.

Supplies of biologically available silica entering waterways come largely from weathering of soils and sediments. Human activities over the past few decades have tended to decrease the delivery of useable silica to coastal marine systems by spurring eutrophication upstream, which tends to trap silica before it reaches the coast. Thus, the concentration of silicate in Mississippi River water entering the Gulf of Mexico decreased by 50 percent from the 1950s to the 1980s even as nitrate fluxes and concentrations increased. Even the silica that reaches the coast can quickly become unavailable if eutrophication leads to diatom blooms. As the diatoms die and fall to the bottom, their silica-rich shells remain stored long term in bottom sediments.

A decrease in silica availability, particularly if combined with increases in N, may encourage some harmful algal blooms as competition with diatoms is decreased. In all cases where long-term data are available on silica in coastal waters, a decrease in silica relative to N or P has been correlated with an increase in harmful algal blooms.

SOURCES OF NUTRIENTS TO COASTAL ECOSYSTEMS

Human activities profoundly influence the global cycling of nutrients, especially movement of nutrients to estuaries and other coastal waters. For instance, human activity has more than doubled the rate of P delivery from land to the oceans. Our effect on N cycling is equally immense, and the rate of change in the human N use pattern is much greater. Our increased reliance on synthetic, inorganic fertilizers has caused the single largest change in the global N cycle. Burgeoning fertilizer use accounts for more than half of the total human-driven alteration of the N cycle.

The process for making inorganic N fertilizer was invented during World War I, but was not widely used until the 1950s. The rate of fertilizer use increased steadily until the late 1980s, when the collapse of the former Soviet Union led to great disruptions in agriculture and fertilizer applications in Russia and much of Eastern Europe. These disruptions led to a slight decline in global N fertilizer use for a few years. By 1995, however, global use of inorganic N fertilizer was again growing rapidly, with much of the growth driven by China. Annual fertilizer use by 1996 totaled approximately 83 teragrams (Tg), where one teragram equals a million metric tons of N. Approximately half of the inorganic N fertilizer that has ever been used on earth has been applied during the past 15 years.

Although fertilizer production and use is the human activity that mobilizes the largest amount of N worldwide, other human-controlled processes also convert atmospheric N into biologically available forms. These activities include the burning of fossil fuels such as coal and oil and extensive plantings of nitrogen-fixing crops such as soybeans, peas and alfalfa.

Human fixation of N from all these activities increased by two- to three-fold from 1960 to 1990 and continues to grow. By the mid 1990s, human activities made new N available at a rate of some 140 Tg per year, matching the natural rate of biological nitrogen fixation on all the land surfaces of the earth. Thus, the rate at which humans have altered N availability far exceeds the rate at which we have altered the global carbon cycle, driving up the carbon dioxide concentration in the atmosphere and perhaps setting in motion a warming of the earth's climate.

Human-driven changes in nutrient cycling have not occurred uniformly around the world. The greatest changes are concentrated in the areas of high human population density and intensive agricultural production. Some regions of the world – such as the Hudson's Bay area of Canada — have experienced very little change in the flows of either N or P to the coast, while other places have experienced tremendous changes. Human activity is estimated to have increased N fluxes down the Mississippi River by more than 4-fold; into the coastal waters of the northeastern United States generally, and Chesapeake Bay specifically, by some 6- to 8-fold; and into the rivers draining to the North Sea by 11-fold (Figure 6). Trends over time also vary among regions. For example, while the global use of inorganic N fertilizer continues to increase, its use in the United States has risen very little since 1985.

Wastewater vs. Nonpoint Sources of Nutrients

Point-source wastewater flows can sometimes be the major source of N to an estuary when the watershed is heavily populated and small relative to the size of the estuary itself. Even in some estuaries fed by runoff from larger watersheds, sewage wastewater can be the largest source of N if the watershed is heavily populated. For example, wastewater contributes an estimated 60 percent of the N that enters Long Island Sound, largely because of sewage discharges into the sound from New York City. In most estuaries, however, N and P inputs from nonpoint sources are greater than those from wastewater, particularly in estuaries that have relatively large watersheds and thus more rural land devoted to crop and livestock production as well as more area to trap N pollution from the atmosphere. For example, only one quarter of the N and P inputs to Chesapeake Bay come from wastewater treatment plants and other such point sources. For the Mississippi River, sewage and industrial point sources supply an estimated 10 to 20 percent of the total N and 40 percent of the total P contribution.

Agriculture as a Source of Nutrients

For P, agriculture is one of the largest sources of nonpoint pollution. For N, both agriculture and burning of fossil fuels contribute significantly to nonpoint flows to estuaries and coastal waters. N from these sources can reach the water either by direct leaching or runoff from farm fields or indirectly, through the atmosphere. Some N is leached directly from agricultural fields to groundwater and surface waters. A significant amount of the N from agricultural sources, however, travels on the wind. Globally, some 40

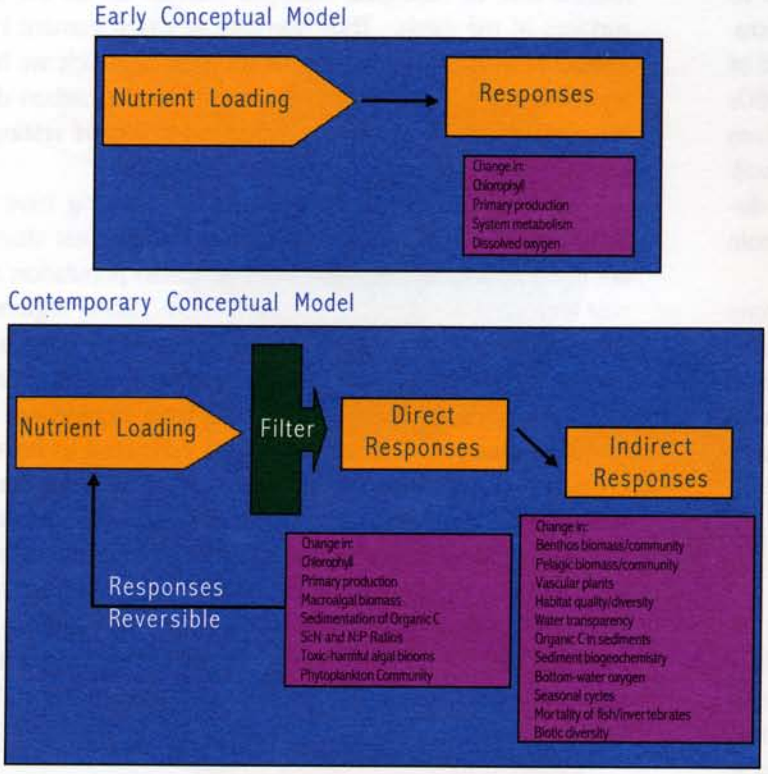


Figure 9 - Our understanding of the complexity of responses by coastal ecosystems to human-caused nutrient enrichment has grown considerably in the past decade. Our earlier conceptual model focused on direct responses of coastal waters, such as stimulation of phytoplankton blooms. The contemporary conceptual model reflects a growing awareness of the complexity of the problem, including recognition that the attributes of specific bodies of water (rate of mixing between top and bottom waters, frequency of flushing with open-ocean water, clarity, grazing pressure on algae) create enormous variations in their responses to nutrient loading and lead to a cascade of direct and indirect effects. Further, experience has shown that appropriate management actions to reduce nutrient inputs can reverse some of the degradation caused by enrichment. (Redrawn from Cloern, 2000).

percent of the inorganic N fertilizer that is applied to fields is volatilized as ammonia and lost to the air, either directly from fertilizer or from animal wastes after crops grown with the fertilizer have been fed to chickens, pigs, or cattle. In the United States, the value is somewhat lower, but still 25 percent of the inorganic N fertilizer used is eventually volatilized to the atmosphere. This N, as well as the nitrogen-based trace gases such as nitric oxide released during fossil-fuel combustion, is later deposited onto the landscape as acid rain or dry pollutants, which can run off into waterways. Thus, in contrast to P, the amount of N exported into coastal waters from non-agricultural landscapes, including forests, can be substantial.

Agriculture in the United States and other developed countries has changed tremendously over the past 30 to 50 years as production systems have become more specialized and concentrated. Overall agricultural production has more than doubled, yet production is occurring on less land and on fewer but larger farms. There has been an attendant increase in the intensification of the poultry, beef, and hog industries.

Prior to World War II, farming communities tended to be self-sufficient, in the sense that enough feed was produced locally to meet animal requirements, and manure from the livestock could be recycled to meet crop fertilization needs. After the war, increased fertilizer availability and use, along with society's demand for cheap meat and milk supplies, encouraged the decoupling of grain and animal production systems. Grain production could now be sustained with inorganic fertilizer inputs. Meanwhile, livestock producers could purchase feed commercially rather than raise crops on site to nourish their animals. By 1995, the major livestock-producing states imported more than 80 percent of their grain for feed, and less than a third of the grain produced on farms today is fed to animals on the farm where it is grown

This evolution in agriculture has resulted in a major transfer of nutrients from grain-producing areas to animal-producing areas and, consequently, an accumulation of N and P in soils of the animal-producing areas (Figure 7). Unfortunately, this excess of nutrient-laden manure has tended to build up in areas with marginally productive lands, and as a result, these areas have a limited capacity to make use of the nutrients in manure in crop production. This fact has exacerbated the problem of nonpoint runoff of manure nutrients into watersheds and ultimately, coastal waters. Animal wastes also contribute greatly to ammonia inputs to the atmosphere, and when this N is deposited back onto the landscape, it can be a significant source of N to surface and ground waters that flow into coastal marine ecosystems.

On average in the United States, the amount of ammonia volatilized to the atmosphere from agricultural systems is roughly equivalent to the amount of nitrate that leaches from crop fields into surface waters. Because this airborne N comes in addition to the nutrients that animal wastes leak directly to surface waters, animal wastes may be the largest single source of N that moves from agricultural operations into coastal waters.

Fossil-fuel Combustion as a Source of Nitrogen

The byproducts of fossil-fuel combustion – principally exhaust from motor vehicles and electric-power generation – are a major source of N to coastal waters in many regions. This includes both direct deposition of airborne N onto the surface of coastal waters and deposition onto the landscape, where it subsequently washes or leaches into rivers or groundwater that flows into coastal ecosystems. The limited evidence available indicates that direct deposition of airborne N onto the water surface alone contributes from 1 percent to 40 percent of the total N entering an estuary, depending to a large extent on the size of the estuary relative to its watershed. In general, the larger the estuary is relative to its watershed, the greater the percent of N that is deposited directly onto the water.

For estuaries that are small relative to the size of their watersheds, N deposition from the atmosphere onto the landscape, with subsequent runoff into the estuary, is probably a greater source than deposition of N directly onto the water surface. Unfortunately, the magnitude of this input is poorly characterized for most estuaries.

Determining Sources of N to Specific Estuaries

Currently, there are no uniformly accepted methods for determining sources of N to an estuary, and thus great uncertainty remains about the importance of atmospheric deposition in delivering N to specific estuaries.

The amount of N deposited onto a landscape can be estimated for most watersheds, although such estimates are subject to considerable error because of inadequate monitoring and the difficulty of measuring dry deposition of N pollutants. A larger problem, however, is determining what portion of the N is retained in the landscape and what portion is actually exported to rivers and ultimately the coast.

There are two major approaches for making this determination: statistical models and process-based models. In their application to estuaries, both of these computer modeling approaches are quite recent and relatively untested, and there is an urgent need for further development and evaluation of these techniques. So far, however, it appears that statistical models have produced more reliable estimates of N retention in watersheds. These models suggest that in areas where atmospheric deposition of N is moderately high, as is true over most of the northeastern United States, an average of 40 percent of that deposition is exported from the landscape to downstream ecosystems. Process based models tend to assume that a much smaller percent of N deposition is exported downstream, but these models do not consider export of all forms of N (dissolved organic N as well as nitrate). Yet recent evidence indicates that for most temperate forests, more N is exported in organic forms than as nitrate.

The lack of well-accepted techniques for quantifying various N sources to an estuary makes it difficult to determine accurately the relative role of fossil-fuel burning versus agricultural activity in nutrient pollution of specific coastal ecosystems. Nevertheless, the relative importance of these two activities in controlling atmospheric deposition of N to estuaries clearly depends on the nature and extent of farming activities in the watershed as well as the nature and extent of fossil-fuel combustion in the airsheds upwind of the watershed (Figure 8).

In estuaries fed by watersheds with little agricultural activity but significant loads of atmospheric pollution – for example, the Connecticut and Merrimack rivers and most of the northeastern United States — atmospheric deposition of N from fossil-fuel combustion can account for up to 90 percent or more of the N contributed by nonpoint sources. For many estuaries, including Chesapeake Bay, both agricultural sources and fossil-fuel sources are significant contributors of N. On the other hand, for watersheds such as the Mississippi River Basin, where agricultural activity is high and atmospheric pollution from fossil fuel burning is relatively low, agricultural sources dominate the export of N. Interestingly, the major hot-spots of agricultural activity that dominate the N inputs for the Mississippi and Gulf of Mexico appear to be far upstream from the Gulf, in Iowa, Illinois, Indiana, Minnesota, and Ohio.

STEPS TOWARD SOLUTIONS

According to a recently completed National Estuarine Eutrophication Assessment by the National Oceanic and Atmospheric Administration, more than half of the coastal bays and estuaries in the United States are degraded by excessive nutrients, primarily N. The NRC "Clean Coastal Waters" report called for a 20-year national effort to reverse this trend and begin the restoration of our coastal marine ecosystems. At a minimum, the report called for restoring 10 percent of the degraded systems by 2010 and 25 percent by 2020. In addition, the report recommended that steps be taken to ensure no coastal areas ranked as healthy are allowed to develop symptoms of nutrient over-enrichment.

Meeting these goals will require a multitude of strategies and approaches tailored to specific regions and ecosystems (Figure 9). For some coastal systems such as Long Island Sound, N removal during sewage treatment will be required. Although sewage treatment in the nation has greatly improved since the passage of the Clean Water Act in 1972, the major focus has been on removing organic matter (secondary treatment). Many sewage treatment plants have also instituted P removal for protection of freshwater systems. Yet N removal during sewage treatment remains much less common.

For most coastal systems, however, human sewage is not the major source of nutrients, and other control strategies will be required. N and P from animal wastes in livestock feedlot operations are one of the biggest sources of nutrients to coastal waters in many areas. In contrast to human sewage, these animal wastes receive little if any treatment and remain largely unregulated. Yet the waste from hog production in North Carolina alone is 3-fold greater than all the human sewage output from New York City. Technologies exist for treating animal wastes to remove nutrients and for eliminating volatilization of ammonia from these wastes to the atmosphere.

A variety of control strategies are available to reduce fertilizer runoff from agricultural lands and emission of N compounds from fossil fuel combustion. Fossil-fuel emissions are already regulated under the Clean Air Act, although coastal N pollution was not considered in framing that law. Greater regulation, federal oversight, and incentives for compliance will all be required if these control strategies are to be better directed towards solving pollution problems of coastal rivers, bays, and seas.

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About the Science Writer

Yvonne Baskin, a science writer, edited the report of the panel of scientists to allow it to more effectively communicate its findings with non-scientists.

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