Enriching the Sea to Death

by Scott W. Nixon

An excess of nutrients flowing from the land into the sea has created serious environmental problems in many coastal waters. Only recently have measures been taken to forestall the worst effects

The widespread pollution of Narragansett Bay began with a great celebration on Thanksgiving Day, 1871. For 10 full minutes, the church bells of Providence, R.I., rang out, and a 13-gun salute sounded. The townspeople were giving thanks for the completed construction of their first public water supply. Soon afterward clean water flowed through taps and flush toilets, liberating residents forever from back-breaking trips to the well and freezing visits to the privy. Millions learned the joys of running water between about 1850 and 1920, as towns throughout North America and Europe threw similar parties. But homeowners gave scant thought to how their gleaming new water closets would change the makeup of the oceans.

With the wonder of running water came the unpleasant problem of running waste. No longer was human excrement deposited discreetly in dry ground; the new flush toilets discharged streams of polluted water that often flowed through the streets. Town elders coped with the unhappy turn of events by building expensive networks of sewers, which invariably routed waste to the most convenient body of water nearby. In this way, towns quickly succeeded in diverting the torrent of waste from backyards and city streets to fishing spots, swimming holes and adjacent ocean shores. In many cases, the results were disastrous for the aquatic environment. And as the flow continues, society still struggles with the repercussions for the plants and animals that inhabit coastal waters.

Untamed Growth

Even a century ago the unsightly consequences of dumping raw sewage directly into lakes and bays were quite troubling. Dead fish and malodorous sludges fouled favorite beaches as sewage rode back toward land on the waves. Unwilling to return to the days of chamber pots and privies, people were soon forced to clean up their waste somewhat before discharging it.

The wastewater-treatment technologies put into place between about 1880 and 1940 removed visible debris and pathogenic organisms from sewer effluent, effectively eliminating the distasteful reminders that had once washed up on the shore. By the 1960s many treatment plants had begun to remove organic matter as well. But the various methods failed to extract the elements nitrogen and phosphorus, nutrients indispensable to human life and abundant in human waste. These invisible pollutants were flushed into rivers, lakes and oceans in prodigious quantities, and no telltale sign heralded the harm they could inflict.

As every farmer and gardener knows, nitrogen and phosphorus are the essential ingredients of plant fertilizers. Plants that live underwater often respond to these nutrients just as beets and roses do: they grow faster. Of course, aquatic plants are different from the trees and shrubs familiar to landlubbers—most are microscopic, single-celled organisms called phytoplankton that drift suspended in the currents.

Where nutrients are scarce, phytoplankton are sparse and the water is usually crystal-clear. But in response to fertilization, phytoplankton multiply explosively, coloring

BLOOM OF PHYTOPLANKTON colors a stretch of Japanese coastline a vivid hue. Dissolved nutrients shed from land cause the growth of such blooms, which can deprive life at lower depths of light and oxygen.

SUSAN AVIATION

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FOREST BUFFERS prevent plant nutrients in the runoff from these agricultural lands from going directly into Chesapeake Bay.

Getting the Nutrients Out

by Mia Schmiedeskamp

North Americans pour nutrients into bays and estuaries at alarming rates. Is there any way to kick this century-old habit? Recent efforts in some of the hardest-hit areas—the coastlines of Florida, North Carolina and Chesapeake Bay—show that the answer is yes.

The first line of attack is effective sewage treatment. Nitrogen can be removed from wastewater through denitrification, a process carried out by bacteria native to sewage. When wastewater managers cater to these microbes' preference for lots of food and little oxygen, the "bugs" consume troublesome nitrates and belch out harmless nitrogen gas.

Denitrification can be cost-effective as well as good for the environment. "We already see many facilities in our watershed implementing [it] even where they aren't required to," says Allison P. Wiedeman of the Environmental Protection Agency's Chesapeake Bay Program. Although capital expenditures can run from about $1 million to retrofit a modern plant to some $20 million for a complete redesign of an older one, savings in operation and maintenance offset costs over the long term.

The additional microbial treatment step cuts down on the time energy-guzzling fans must be run to aerate the sewage, for

the water shades of green, brown and red with their photosynthetic pigments. These blooms increase the supply of organic matter to aquatic ecosystems, a process known as eutrophication.

Pollution-driven eutrophication was not recognized as a serious threat to many larger lakes in Europe and North America until the 1950s and 1960s—Lakes Erie and Washington in the U.S. are well-known examples. Why was the accelerating growth of phytoplankton a concern? After all, people welcomed the "green revolution" that fertilizers helped to bring to agriculture around that time. The difference underwater results from the precarious balance between oxygen supply and demand in aquatic ecosystems.

Terrestrial ecologists do not usually worry about oxygen, because the air is full of it: each cubic meter contains some 270 grams. And the atmosphere is constantly in motion, replenishing oxygen wherever it is used. But water circulates less readily than air and holds only five to 10 grams of oxygen per cubic meter at best—that is, when freely exchanging its dissolved gases with the atmosphere. Although fish and a number of other aquatic animals have adapted to live under these conditions, a small decrease in the oxygen content of their surroundings can often be deadly to them.

Phytoplankton floating near the surface of nutrient-rich lakes fare better in the oxygen equation. They receive ample sunlight to carry out photosynthesis during the day and have access to plenty of oxygen to support their metabolism at night. But even under the best circumstances, phytoplankton are short-lived: the tiny organisms continually die off and sink, leaving new generations growing in their place. The more abundant the bloom, the heavier the fallout to the lower depths. And therein lies the problem: the bottom-living bacteria that digest this dead plant matter consume oxygen.

COURTESY OF FUNEN COUNTY COUNCIL DEPARTMENT OF TECHNOLOGY AND ENVIRONMENT instance. Denitrification also modulates the acidity of wastewater, making some chemical additives unnecessary, and reduces the amount of sludge that must be disposed of. Currently 43 treatment plants in the Chesapeake Bay watershed have been converted to denitrification, and plans are under way to outfit 58 more in the next five years. "In the early part of the next millennium, [denitrification] is going to be standard," Wiedeman predicts.

Yet reducing nitrogen in sewage alone will not do the entire trick. In the Chesapeake Bay watershed, for instance, the goal is to reduce nutrient load by 40 percent—but only 25 percent of the nitrogen comes from sewage. Much of the rest is runoff from farmlands. Efforts to stem this flow take two forms, explains Russell L. Mader of the Chesapeake Bay Program's nutrient subcommittee: reducing the total amount of fertilizer applied to fields and keeping it where it belongs.

Land management is the key to the latter goal. "We work to minimize high-velocity flows of water that strip away soil and nutrients," Mader says. This end can be achieved by proper grading of farmland and by tillage that minimizes soil disturbance, leaving a mat of plant debris to protect the surface. And forests or artificial wetlands can serve as a buffer between field and stream, providing a place for sediments to settle from runoff and for plants to take up dissolved nutrients.

Fertilizer-reduction strategies, on the other hand, are geared at giving crops as much nutrient as they need but no more. Methods range from simple soil tests to computerized tractors that use satellite-based navigation equipment to direct the application of fertilizer. Mader estimates that in the Chesapeake Bay watershed alone, about 600,000 hectares (1.5 million acres) are already under various forms of nutrient management.

But some of the toughest problems are just now being recognized. Regions with high concentrations of livestock farming—where fields are fertilized by manure—are becoming overloaded with phosphorus even when their nitrogen needs are perfectly met. Reducing the phosphorus burden on the soil will leave farmers with a lot of excess manure; one of the emerging questions of nutrient management is what to do with the stuff.

Tampa, Fla., was one of the first cities to tackle the nutrient problem, with dramatic effect. In the late 1970s the city embarked on an ambitious program to restore normal life to its polluted bay, instituting a regimen of nitrogen removal from sewage and of wastewater recycling by local fertilizer manufacturers.

J. O. Roger Johansson of the city's Bay Study Group has monitored the progress since 1978. "We reduced the amount of nitrogen going into the bay by about half," he notes. "It took about two years to expend the nutrients already in the bay's sediments, and then the phytoplankton population dropped by half." Lower phytoplankton counts have been followed by fewer days without oxygen in the depths and by the return of sea grasses to the shallow waters. This bay, which was nearly ruined by human imposition, has been rescued by human intervention—good news for the Chesapeake and the many other waters still in harm's way.

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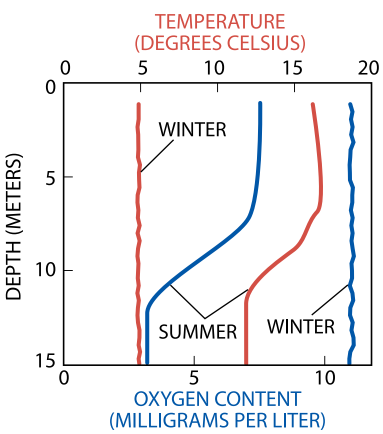
When organic material is abundant in a lake and where surface and bottom waters seldom mix—for example, where winds are calm—oxygen rapidly becomes scarce below the surface. Animals that cannot escape to better-aerated zones will suffocate, and dead creatures may begin to litter the shoreline as bacteria take over the otherwise barren bottom waters. During the 1970s, such awful conditions used to regularly overcome oxygen-starved Lake Erie, which was said to be "dying."

SEA GRASS is smothered by the macroalgae growing in shallow Danish waters enriched with nutrient runoff from farms and sewers (*left*). In winter, the water is well mixed, and oxygen levels are uniform throughout (*below*). In summer, warm, sluggish surface water floats on top of cooler, saltier bottom water, which rapidly becomes depleted of oxygen as phytoplankton decay.



LAURIE GRACE; SOURCE: FUNEN COUNTY COUNCIL

Dead Zones

Until about 40 years ago, the oceans were thought to be immune to the combined forces of nutrient enrichment and oxygen depletion, which were then commonly observed at work in lakes. After all, the seas are vast and restless—the waste discharged from land seemed just a drop in a giant, sloshing bucket.

Scientists now know this assumption was wrong. The fertilization of coastal waters constitutes a major environmental threat to the Baltic Sea, the Gulf of Mexico, Chesapeake Bay, the Lagoon of Venice, the North Sea and a great many other estuaries, bays and lagoons in the industrial world. Most at risk are sheltered regions that do not experience winds or tides strong enough to keep the sea thoroughly mixed the whole year around. For just like nutrient-rich lakes, polluted bays and estuaries can become starved of oxygen when their bottom waters are cut off from the atmosphere.

Coastal areas are especially vulnerable to oxygen depletion because freshwater draining into the ocean from rivers and streams—often laden with nutrients—tends to float on top of denser saltwater. In summer, the surface layer becomes even more buoyant as it warms in the sun. Unless some energetic mixing ensues, the lighter, oxygen-rich veneer will remain isolated from the denser water below. In areas of weak wind and tide, such stratification can last an entire summer.

When a polluted bay or estuary remains relatively still for weeks, months or whole seasons, the difference between life at the top and life at the bottom becomes stark. The surface waters, rich in nutrients and bathed in sunlight, teem with phytoplankton and other forms of floating plant life. The bottom layers become choked with dead plant matter, which consumes more and more oxygen as it decomposes. Below the surface, entire bays can suffocate. And the problem is not necessarily limited to protected waters near the shore. Where enough nutrients arrive and currents are configured just right, even open waters can fall victim. For instance, oxygen deprivation cuts a lethal swath through some 18,000 square kilometers (7,000 square miles) of the deep waters of the Gulf of Mexico every summer, creating a barren region called the "dead zone."

The effects of eutrophication trickle up into human affairs in various ways. Bays and estuaries provide some of the richest fishing grounds, yet oxygen depletion kills fish, and nutrients may cause certain toxic varieties of phytoplankton to bloom, contaminating the shellfish that feed on them. Picturesque shores are sullied by dead fish and rotting plant waste, and the water may reek of rotten eggs as bacteria on the ocean floor spew out hydrogen sulfide.

Fertilization of coastal waters also changes life underwater in more subtle ways. For example, as the balance of nutrients changes, the mix of phytoplankton may shift in response. In particular, diatoms, which need about as much silicon as nitrogen, cannot benefit. Because pollution increases the supply of nitrogen but not the amount of silicon, these important organisms may be crowded out by other species of phytoplankton that are less useful to feeding fish and shellfish.

What is more, sunlight does not penetrate deeply into water clouded by blooms. Thick layers of phytoplankton may shade out the sea grasses and seaweeds that typically grow in coastal waters and shelter vulnerable creatures such as crabs and young fish. As a result, complex aquatic food chains may be broken apart.

Cattle, Corn and Cars

The assault on the waters of the developed world that began with urban sewage systems in the mid-1800s has only escalated since that time. Because nitrogen and phosphorus are essential for human nutrition, the rapidly growing world population consumes—and excretes—ever larger amounts of both elements. This factor alone almost doubled the release of nutrients from human waste between 1950 and 1985. And not only are there more people on the earth but also the typical diet is becoming ever richer in protein. All this protein contains abundant nitrogen, which just increases the burden on the environment when it is metabolized and finally excreted.

As the human population has skyrocketed, so has the number of animals raised for food. The count of livestock—animals that also consume and excrete large amounts of nitrogen and phosphorus—has grown by 18 percent during the past 20 years. To produce the huge quantities of crops needed to feed both humans and livestock, farmers have been applying exponentially increasing amounts of fertilizer to their fields since the 1950s. The main ingredients in these fertilizers are nitrogen and phosphorus. Rain washes these nutrients off the land and into rivers and streams, which then carry them to lakes and oceans.

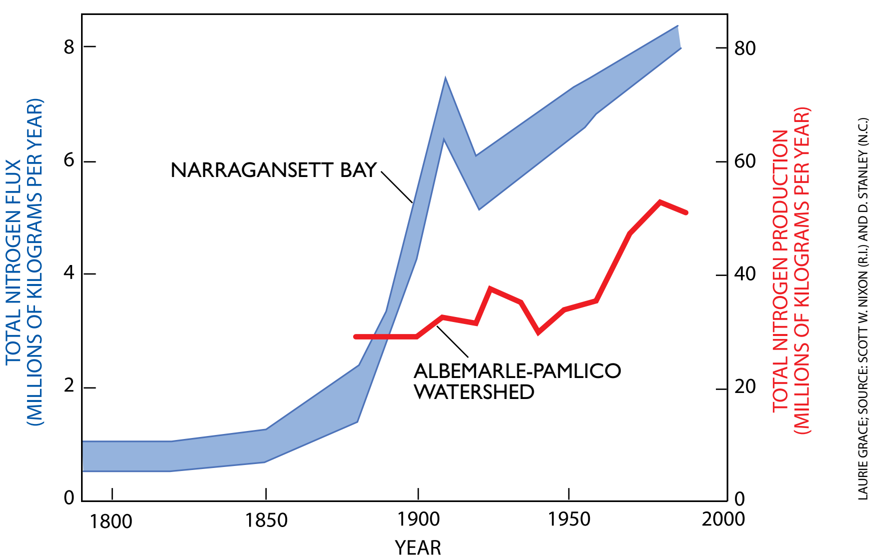
Between 1960 and 1980 the application of nitrogen fertilizer increased more than fivefold, and in the decade that followed, more synthetic fertilizer was spread on land than had been applied throughout the entire previous history of agriculture. Farmers have also been raising increasing quantities of legumes (such as soybeans), which live in partnership with microorganisms that convert nitrogen to nutritive forms. Vast quantities of enriching nitrogen compounds—perhaps equal to half of what is produced as fertilizer—have become available from this source.

That there have been widespread changes in the oceans is not surprising. The dead zone that forms in the Gulf of Mexico every summer probably results from excess fertilizer washed from farms and carried down the Mississippi. Unfortunately, such nutrient injections may be even more dangerous to coastal waters than to lakes. Research early on showed that phosphorus rather than nitrogen induces aquatic plants to bloom in most freshwater environments. This news was in a sense good for lakes, because phosphorus is more easily managed than nitrogen.

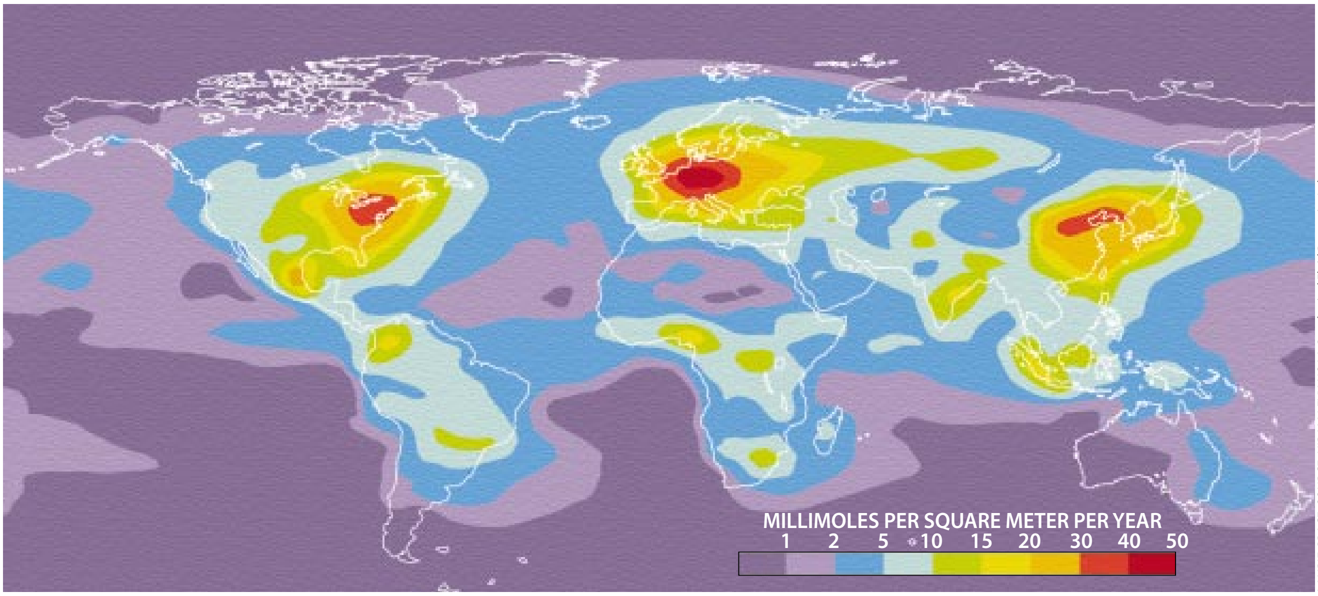
Phosphorus is chemically sticky and binds easily to other substances. Thus, it tends to adhere to soil and is less likely than nitrogen to leach out of fertilized fields. And phosphorus can be easily removed from sewage by taking advantage of the same stickiness: during treatment, chemicals are added that bind up the element and then settle out along with other sludge. Largely because of improved phosphorus removal from sewage and a widespread ban on the use of phosphate in products such as laundry detergent, the eutrophication of many lakes and rivers has been stopped or greatly reduced.

There is increasing evidence that the phytoplankton of most temperate estuaries, bays and other coastal ocean waters respond not so much to phosphorus as to nitrogen. Marine scientists still do not fully understand the reasons for this difference, but the implications are quite profound. Nitrogen washes easily from fertilized fields into streams and rivers; many sewage-treatment plants are not yet configured to remove nitrogen from wastewater; and there is an additional, copious supply of nitrogen to the oceans—the atmosphere.

Lightning has always converted a tiny amount of inert nitrogen gas, which makes up 78 percent of air, into soluble compounds that plants can take up in their roots and metabolize. But the combustion of fossil fuels has unleashed a torrent of such nitrogen compounds into the atmosphere. When oil, gas and coal burn at high temperatures in engines and electric-power generators, they produce nitrogen oxides. Rain and wind carry these soluble compounds to the earth, further enriching coastal waters already replete with sewage and agricultural runoff. In all, fos-



NITROGEN LEVELS in Narragansett Bay, R.I., increased dramatically before the turn of the century, after installation of a public water supply and sewer system. Certain other watersheds did not experience a sharp rise in nitrogen levels until fertilizer use took off in the 1950s and 1960s; an example is the Albemarle-Pamlico watershed in North Carolina.



LAURIE GRACE; SOURCE: HIRAM LEVY *NOAA Geophysical Fluid Dynamics Laboratory*

ATMOSPHERIC DEPOSITION of reactive nitrogen has large geographic variations over the continents and oceans, as shown by computer modeling (*above*). Most of this nutritive nitrogen comes from the combustion of fossil fuels in highly developed areas.

sil-fuel combustion accounts for about 15 percent of the biologically available nitrogen that human activities add to the world every year.

Future Shock

In the 1990s marine eutrophication remains a problem of many wealthy nations. Countries such as the U.S. spend billions on fertilizer, automobiles, power plants and sewer systems, all of which feed nitrogen into the oceans. In fact, the amount of nitrogen available per square kilometer of land from fertilizer application, livestock and human waste alone is currently more than 100 times greater in Europe than in much of Africa.

Fortunately, at least the richer nations may be able to afford high-tech remedies. Sewage-treatment facilities that can eliminate nitrogen from wastewater are springing up, and man-made wetlands and precision application of fertilizers may stem the flow from farms [*see box on page 50*]. But just as people are seeing improvements in some of the worst-polluted coastal waters in the U.S. and Europe, the developing world is poised to repeat what industrial countries experienced over the past 100 years.

Part of the problem will come directly as a result of population growth. With the occupancy of the planet set to reach more than nine billion by 2050, there will be that many more mouths to feed, more fields to fertilize, more livestock to raise and more tons of waste to dispose of. Many experts predict that the release of nutritive nitrogen from fertilizer and fossil-fuel combustion will double in the next 25 years, most of that increase occurring in the developing world.

The United Nations Population Fund estimates that 80 percent of the rise in global population is taking place in the urban areas of Africa, Asia and Latin America. This increase amounts to about 81 million more people every year, a situation akin to spawning 10 cities the size of Moscow or Delhi. Compounding this source of urban growth is the continuing movement of people from the countryside into cities. It was city sewers that first overloaded waterways such as Narragansett Bay with nutrients, and the scenario is not likely to play out differently in the developing world. Sewers there, too, will likely carry raw sewage initially, and where treatment of these sludges does occur, it will probably not remove nitrogen for many years.

With large stretches of coastline exposed to unprecedented levels of nitrogen, it seems inevitable that ocean waters around the world will become greener, browner and redder and that there will be more frequent periods when the bottom of the sea in vulnerable locations becomes lifeless. Much of the next round of pollution will take place in the waters of the tropics, where both the corals and the fish that inhabit these delicate ecosystems are at risk. Yet it remains difficult to gauge exactly how damaging this inadvertent fertilization will ultimately prove. Scientists are still far from understanding all the ways the oceans will pay for keeping human life so widespread and abundant. But as far as the residents of the ocean are concerned, there seems little cause for celebration. SA

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Further Reading

Coastal Marine Eutrophication: A Definition, Social Causes, and Future Concerns. Scott W. Nixon in *Ophelia*, Vol. 41, pages 199–219; February 1995.

Global Population and the Nitrogen Cycle. Vaclav Smil in *Scientific American*, Vol. 277, No. 1, pages 76–81; July 1997.

Global Nitrogen Overload Problem Grows Critical. A. S. Moffat in *Science*, Vol. 279, pages 988–989; February 13, 1998.