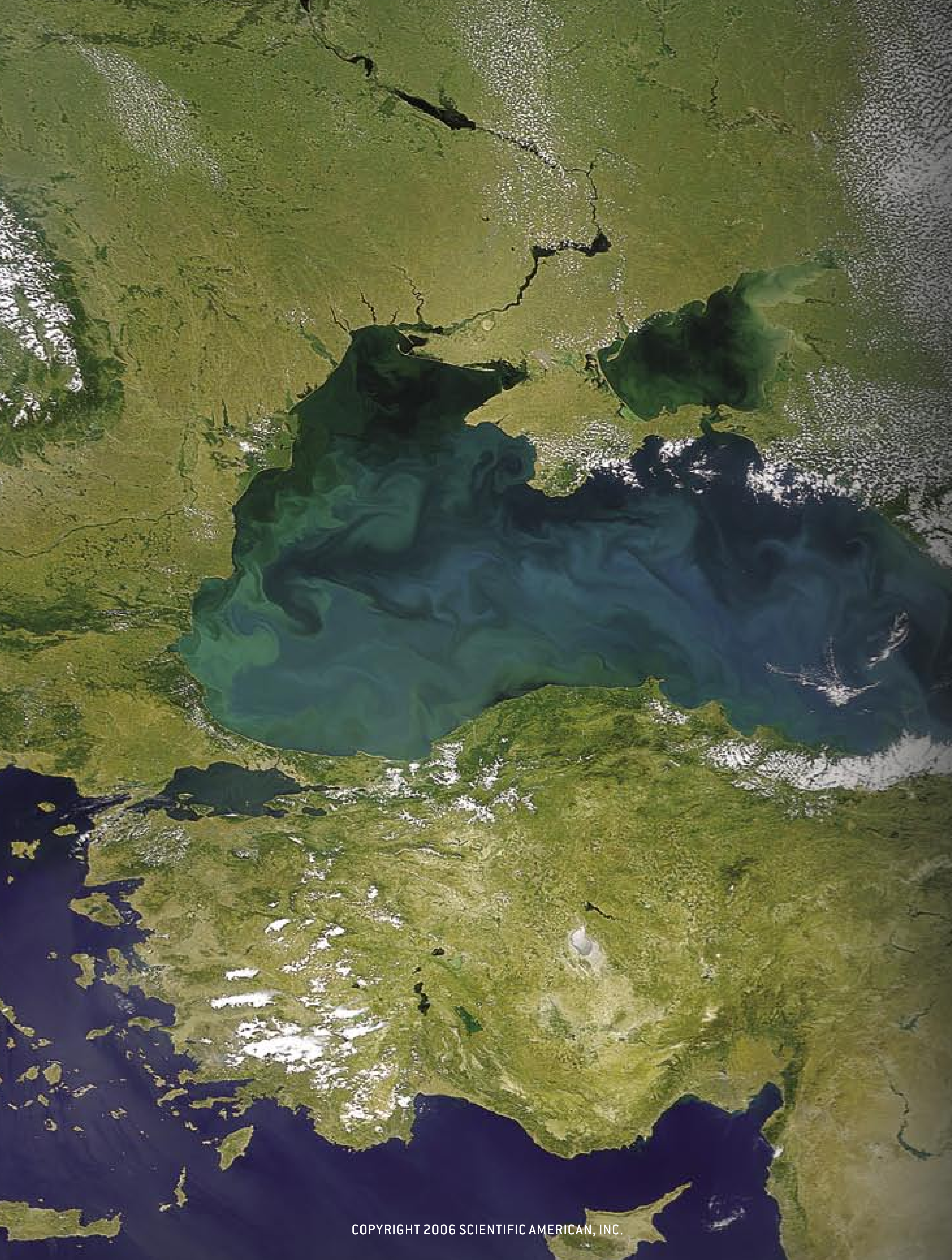
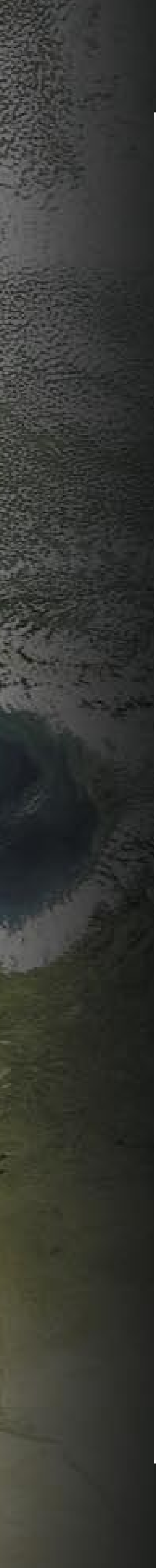




Reviving Dead Zones

BY LAURENCE MEE

How can we restore coastal seas ravaged by runaway plant and algae growth caused by human activities?

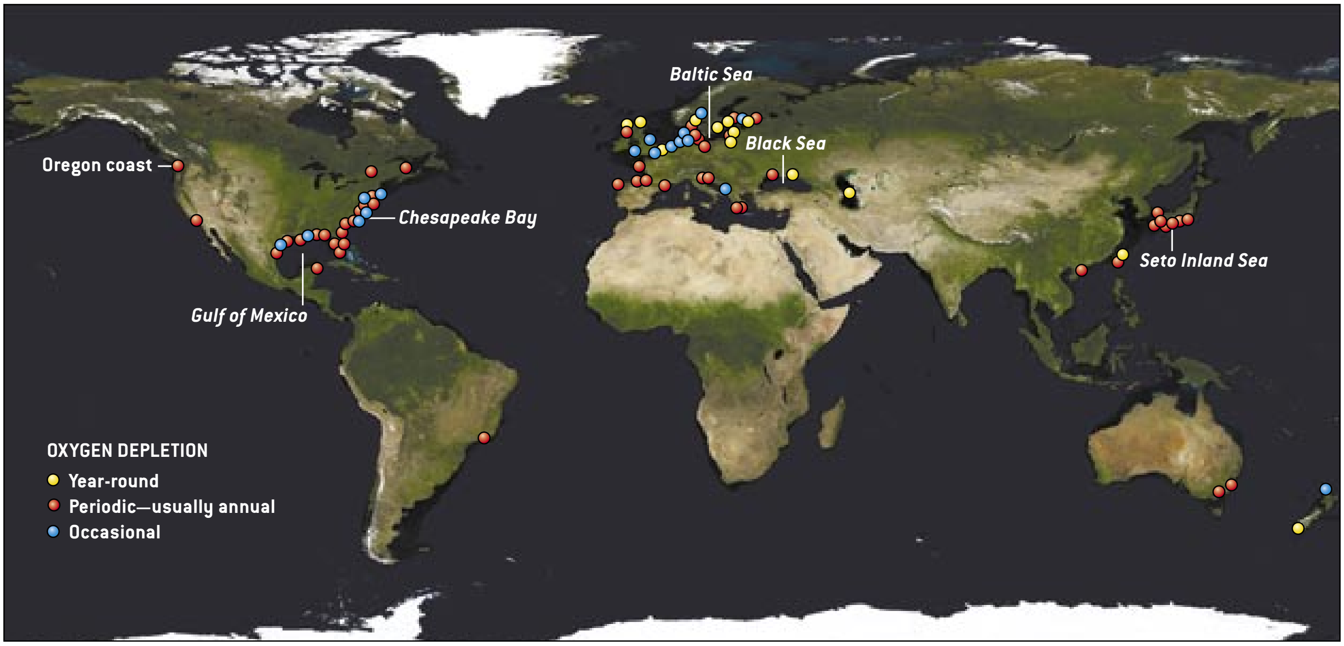
Imagine a beach crowded with vacationers enjoying the hot summer sun. As children paddle about in the shallows, foraging for shells and other treasures, dead and dying animals begin to wash ashore. First, a few struggling fish, then smelly masses of decaying crabs, clams, mussels and fish. Alerted by the kids' shocked cries, anxious parents rush to the water to pull their children away. Meanwhile, out on the horizon, frustrated commercial fishermen head for port on boats with empty nets and holds.

This scene does not come from a B horror movie. Incidents of this type actually occurred periodically at many Black Sea beach resorts in Romania and Ukraine in the 1970s and 1980s. During that period an estimated 60 million tons of bottom-living (or benthic) life perished from hypoxia—too little oxygen in the water for them to survive—in a swath of sea so oxygen-deprived that it could no longer support nonbacterial life.

At its extreme in 1990, the "dead zone," located in the northwestern part of the sea off the mouth of the Danube River, extended over an area the size of Switzerland (40,000 square kilometers). On the other side of the world, in the Gulf of Mexico off the Mississippi River delta, another huge dead zone appeared in the mid-1970s, which at its largest reached 21,000 square kilometers. In the past two decades, additional reports of dying or depleted areas in coastal seas and estuaries across the globe have emerged [*see map on next page*].

Determining the causes of this destruction, how it might be prevented and what to do to bring affected areas back to life has been a prime focus of my research since the early 1990s, when I published my first paper on the ecological crisis in the Black Sea. My work and that of others has now revealed important details of the events that degrade coastal ecosystems in many parts of the earth and has turned up new information that could help establish pathways to recovery.

BLACK SEA DEAD ZONE became evident when dying sea life began washing ashore near the mouth of the Danube River in the 1970s. Above, dead fish are left strewn across a Black Sea beach by the high tide. A satellite photograph of the western Black Sea from 2000 (*left*) shows the huge blooms of floating microscopic plants that resulted from the river's nutrient-rich discharge.



DEAD ZONES—areas starved of oxygen (by bacterial decay of overabundant plant growth) and thus of most animal life—occur in coastal seas, often near developed countries. The number of regions affected has doubled since 1990. Polluted runoff from the land often triggers dead zone conditions, although some result naturally. The dead zone in the northwestern Black Sea is now much smaller than it was at its largest a few decades ago.

Dead Zone Formation

OCEAN RESEARCHERS today link the creation of most dead zones to a phenomenon called eutrophication, the overenrichment of the sea by nutrients (principally compounds containing nitrogen and phosphorus) that promote plant growth. A certain amount of these "fertilizers" is essential to the health of phytoplankton—floating algae and other microscopic photosynthesizers that form the base for most marine food chains—as well as for the well-being of the sea grasses and algae that live on the floors of shallow, well-lit seas. But too much of these nutrients in illuminated waters greatly accelerates plant growth, leading to disruptive algal blooms and other unwanted effects.

Plants enter the food chain when tiny seaborne animals (zooplankton), herbivorous fish and filter-feeding bottom dwellers such as mussels and oysters graze them or when they die, decay, fall to the seabed, undergo bacterial decomposition and are incorporated into the underlying sediments. This organic bottom matter feeds the animals living there, including worms, shrimp and some fish.

Normally the numbers of phytoplankton are limited by the availability of light and nutrients and by grazing. But large increases in nitrogen and phosphorus concentrations enable these minute photosynthetic organisms to multiply in great profusion. The water eventually turns green or even brown as phytoplankton populations burgeon, and the shade they cast deprives plants living below them of essential sunlight. Sea grasses in shallow bays also become covered with small attached algae (epiphytes) and can ultimately be smothered and die. Algae can in addition envelop coral reefs, especially where heavy fishing pressure has thinned the ranks of resident grazers.

A major upsurge in the numbers of phytoplankton and epiphytes immediately causes difficulties for nearby sea life, but an even worse situation arises when oxygen levels in bottom waters decline. Lower oxygen concentrations appear when bacteria consume oxygen to break down the masses of organic matter that result from animal wastes and the dead bodies of organisms that multiply during eutrophication. Much of this material accumulates on the seafloor, where oxygen is relatively scarce to begin with.

Oxygen finds its way into the water from either photosynthesis or physical diffusion from the air at the sea surface. Should an area whose bottom is covered with dead plants also feature a strong density gradient that prevents mixing with the overlying water column, the oxygen at the bottom can soon become

Overview/*Coastal Seas in Trouble*

- River-borne plant nutrients from the land are killing off life in parts of shallow seas around the globe, resulting in so-called dead zones.
- Fertilizing chemicals cause microscopic plants floating near the surface to overgrow, depriving any plants living on the bottom of light and leading to large increases in the amount of decaying organic material falling to the seafloor. The bacteria living off the dead organisms use up seafloor oxygen, thereby causing the loss of most animal life there.
- Significant reductions in agricultural and sewage runoff, as well as controls on overfishing, can restore these key marine ecosystems.

THE VISIBLE EARTH/NASA (*satellite image*); RADU MIHNEA (*dead fish*) (*preceding pages*);
THE VISIBLE EARTH/NASA (*satellite image*); SOURCE: BASED ON *UNEP GEO YEARBOOK 2003* (*this page*)

exhausted, leading to the die-off of entire animal communities. (Such gradients can stem from temperature or salinity differences in the water at various depths.) This basic sequence—eutrophication leading to phytoplankton blooms, excess bacterial activity at the bottom, oxygen depletion, and the death of existing plants and animals—has occurred in almost every dead zone examined by researchers.

The details do vary, however, according to the local biological and physical conditions as well as the rate of supply of plant nutrients from the land. Poorly flushed estuaries, for example, are particularly vulnerable to the effects of eutrophication, because low water flows lead to slow replenishment of oxygen in bottom waters. This reduction in oxygen has been a persistent problem along the eastern seaboard of the U.S., where large estuaries, such as the Chesapeake Bay, have been affected.

The excess of nitrogen and phosphorus arriving in coastal seas results in large measure from the changing habits of people living in the areas draining into the sea. Rising fossil-fuel use (which releases nitrogen into the atmosphere), effluent from the mass breeding of food animals and intensive farming, and the construction of sewage systems that empty into bodies of water all lead to greater nutrient emissions into watersheds. The Millennium Ecosystem Assessment released by the United Nations in 2005 reported that the supply of nitrogen-containing compounds to the sea grew by 80 percent from 1860 to 1990. It predicted that the overall outflow to the oceans from human activities will increase by an additional 65 percent by midcentury. Dead zones are thus likely to become even more widespread unless society takes prompt action to reduce plant nutrient runoff.

Watery Graveyard

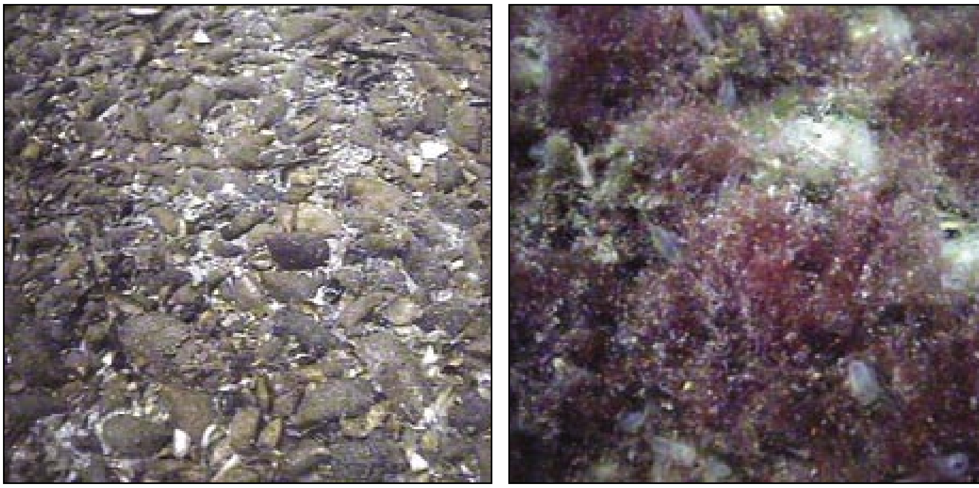
ALTHOUGH EMERGENCE of a dead zone is the final stage of the eutrophication process, marine systems, especially the animal populations, undergo changes long before then. A healthy coastal marine food chain often starts with silica-shelled phytoplankton called diatoms, which are consumed by copepods, minuscule zooplanktonic crustaceans. These animals, in turn, serve as food for fish. Increased nutrient concentrations affect the mix of phytoplankton species such that diatoms often become outnumbered by smaller or less digestible types. When eutrophication produces massive phytoplankton blooms, copepods often are unable to graze on the new, abundant phytoplankton species as well as the large quantities of organic detritus that result from the disruption of the natural ecosystem. This change favors the growth of highly tolerant gelatinous organisms such as *Noctiluca* (responsible for nighttime phosphorescence that occurs when the water surface is disturbed). Biologists sometimes call these jellyfishlike fauna "dead-end species" because higher-level predators have difficulty living off them. Their presence reduces the efficiency of the food chain, leading fish stocks to wane.

Such an imbalance in the food chain can be worsened by intense commercial fishing, particularly where these efforts target high-value "top predator" species such as cod, hake, dorado or horse mackerel. Loss of apex fish species leads to rises in the numbers of small prey fish, which results in fewer zooplankton (the food of the small fish) and, consequently, even more phytoplankton. Scientists call this sequential process "trophic cascading." An inefficient food chain engenders more organic matter on the seafloor, which enhances the risk that a dead zone will follow.

Ecosystems altered by eutrophication also become more vulnerable to invasion by foreign species, which can arrive, for example, in the ballast discharge from transoceanic ships. In the 1980s the comb jellyfish *Mnemiopsis leidyi*, which probably originated off the eastern coast of the U.S., took up residence in the Black Sea. By 1990 this voracious dead-end predator dominated the ecosystem completely, at its maximum attaining an astounding density of up to five kilograms per square meter.

Sometimes shellfish reefs can help stave off degradation of an ecosystem. In many estuaries on the eastern seaboard of the U.S., oysters act as ecosystem engineers by accumulating into huge reefs rising several meters from the seabed; these reefs support a diverse assemblage of organisms, including flounder, snapper, silver perch and blue crabs.

Hunter Lenihan of the University of California, Santa Barbara, and Charles H. Peterson of the University of North Carolina at Chapel Hill have shown, for example, that the tops of oyster reefs in North Carolina's Neuse River became refuges for displaced bottom-water species at the onset of dead zone formation because they projected above the deoxygenated water layer. Mechanical oyster



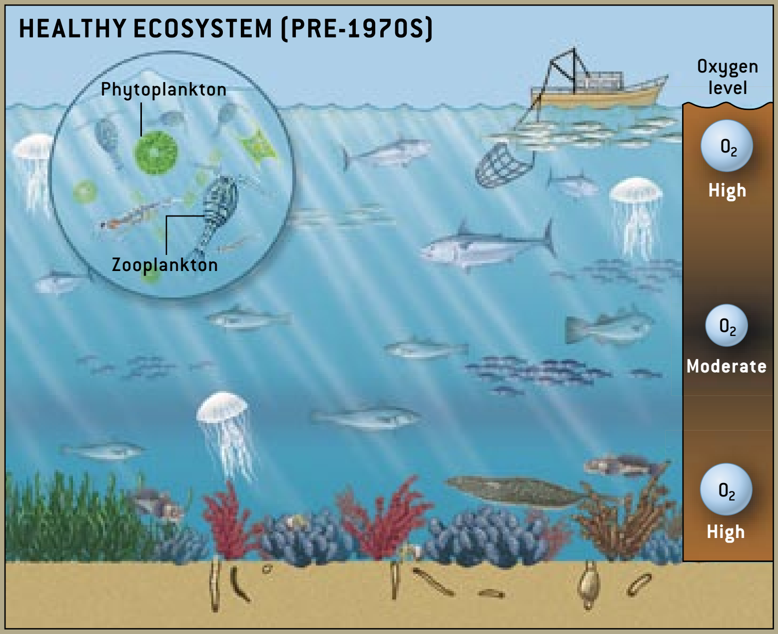
DEAD—AND RECOVERED—BOTTOM LIFE are apparent in these views of two locations on the Black Sea bed earlier this year. The photograph on the left shows a largely depleted area that is covered with the shells of mussels killed by a lack of dissolved oxygen. On the right is a recovering site with a thick and diverse cover of algae and large numbers of ascidians (sea squirts).

TIM STEVENS

KEY STAGES IN THE FORMATION OF A DEAD ZONE

The events underlying the creation of the Black Sea dead zone were fairly typical of how similar oxygen-depleted (hypoxic) areas form, although the details vary from case to case. At the root was eutrophication, an excessive inflow of plant nutrients that resulted in an overgrowth of algae and other small floating photosynthetic plants, which led indirectly to hypoxia and to the death of plants and animals in the lower depths.

The decline of the ecosystem followed three stages described initially by Tatsuki Nagai of Japan's Fisheries Research Agency, who studied one of the first known hypoxic regions. These conditions appeared in Japan's Seto Inland Sea in the early 1960s. He called the natural state the "sea of red bream" (a predator species targeted by local fishers). Then came the "sea of anchovies," when predator species declined, leaving mainly small prey fish behind. Finally, there came a "sea of jellyfish," in which most other species died or fled, leaving highly tolerant invading species dominant. Nagai also was among the first to identify overfishing as a contributor to degradation of the sea's food chain (by removing the top predator fish).



The near-surface coastal waters of the northwestern Black Sea initially contained a diverse mix of phytoplankton (floating algae and other microscopic plants) as well as varied fish and other organisms. Shallow waters close to shore featured shoals of immature anchovies, mackerel and bonito. At the middle depths lived large schools of top predators, such as whiting, and numerous prey fish, plus some jellyfish. At the bottom, communities of mussels as well as gobies, turbot, sturgeon and hermit crabs thrived among extensive meadows of sea grasses and brown and red algae.

SHAWN GOULD

harvesting frequently shortens the height of these reefs, however, which helps to destroy the natural resilience of these ecosystems.

Black Sea Catastrophe

THE BLACK SEA offers a dramatic example of how undersea ecosystems can be destroyed by a surplus of nutrients and also provides insight into how they can be resuscitated. The waters of the northwestern area of the sea fell prey to eutrophication when flows of nitrogen and phosphorus compounds from the land doubled between the 1960s and 1980s. The principal pipeline for these chemicals was the Danube, which drains much of the watersheds in 11 countries across central Europe, from Germany to Romania. The main culprits were agricultural runoff, urban and industrial wastewater, and, in the case of nitrogen compounds, atmospheric transport. At least half the increased nitrogen poured into the Black Sea resulted from modernized farming practices, including intensive use of fertilizers and the establishment of huge animal production facilities. These agricultural activities also contributed to the rise in the phosphorus effluent, but industrial and urban waste discharges laden with polyphosphate detergents played an even more significant role.

THE AUTHOR

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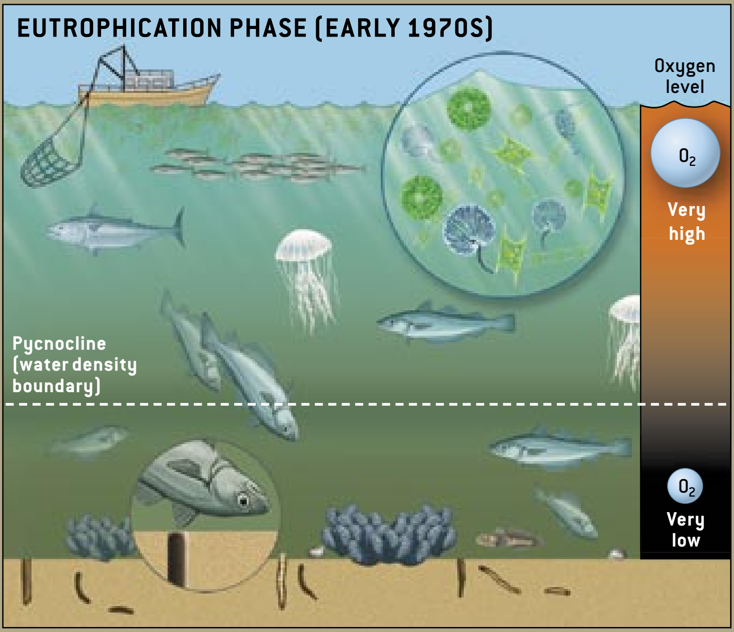
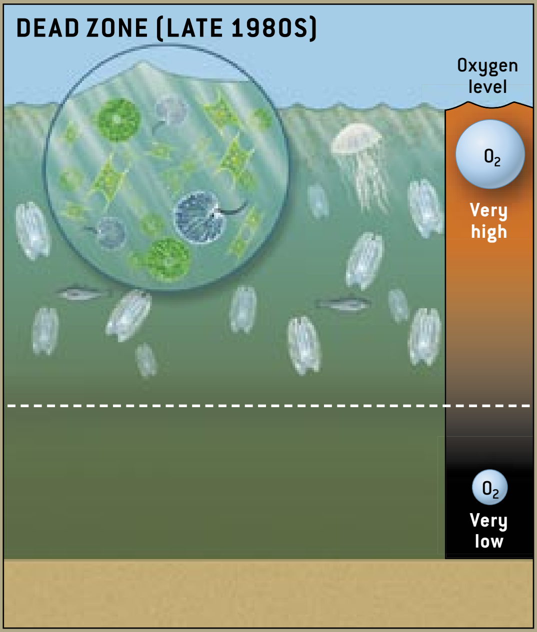
Before the 1960s the shallow northwestern region of the Black Sea was a diverse and highly productive system that included extensive near-shore mats of bottom-living brown algae and, further offshore, the largest red algae community on earth—a field of *Phyllophora* the size of the Netherlands. These natural algae meadows coexisted with enormous beds of mussels and other bivalves, and the whole system supported a large number of invertebrate and fish species. The algae helped to oxygenate the bottom waters, and the mussels filtered the seawater, thereby maintaining good light conditions for photosynthesis. This ecosystem was highly resilient, being able to accommodate large variations in climate conditions and natural disturbances. As nutrient effluents escalated, however, dense phytoplankton blooms appeared in the surface waters. Such luxuriant growth lowered water transparency, which in turn deprived the bottom algae of light



With growing influxes of the nutrients nitrogen and phosphorus from terrestrial runoff, the ecology of the Black Sea coastal region began to change. Massive phytoplankton blooms turned the water green or even brown, depriving plants living below of sunlight and depositing a steady stream of decaying organic matter in the bottom. Bacteria on the seabed then consumed great amounts of oxygen as they feasted on the organic matter and the dead plants, thus producing hypoxia on the seafloor, which killed many organisms.



Eventually, increased shading and rampant hypoxia on the seabed finally left the bottom waters devoid of life. Heavy fishing had already reduced the numbers of predator fish species, and ultimately these and most other large animals disappeared from the area. Opportunistic invading species, notably the comb jellyfish *Mnemiopsis leidyi*, multiplied in great numbers in the upper depths.

and eventually led to their loss, which altered the entire natural ecosystem.

During the summer months, when the water column became stratified, oxygen levels, particularly near the seabed, began to fall. Many of the affected bivalve communities could survive hypoxia for as long as 20 days by closing their shells and living on internal reserves of glycogen—an animal's chief energy-storage carbohydrate. But when these supplies were exhausted, the mollusks died en masse, which led bacteria and other organisms to consume the remaining local oxygen as they degraded the dead animals and to release even more plant nutrients. By the time nearly all the oxygen was gone, all the fauna that normally lived in the area had either migrated away in search of food and oxygen or perished. The region's natural ecosystem was thus seriously degraded.

The area began to recover only when the communist regimes in eastern Europe fell at the end of 1989, ending central economic planning. Suddenly farmers there had little capital to buy fertilizer, so agricultural activities slowed. Likewise, many giant animal farms closed, thus profoundly reducing nutrient runoff. One former pork production facility in Romania with more than a million pigs had generated the equivalent emissions of a city with five million inhabitants.

Within six years the profound dropoff in nutrient influx led to shrinkage of the dead zone [*see box on next page*]. Recovery of the sea bottom, however, was gradual. For example, studies by my Ukrainian colleagues have shown that mussel beds in devastated parts of the northwestern shelf became firmly reestablished only in 2002, many years after other communities had recovered substantially. This past August a research expedition we conducted to examine the state of the sea revealed major reestablishment of benthic algae communities, though generally not the same species that had dominated before the onset of dead zone conditions.

Long Road to Recovery

CLEARLY, RESTORING dead zones requires, at a minimum, reducing nutrient delivery from nearby lands. But marine ecosystems that have collapsed because of eutrophication and hypoxia may not simply bounce back when humans alter their activities to lower the amounts of plant nutrients reaching rivers. This resistance to recovery occurs for three reasons.

River catchments typically possess a huge capacity for storing nutrients—either dissolved in groundwater or adsorbed on soil particles. Years or even decades may pass before nitrogen and phosphorus fertilizers and other chemicals stop leaching out and passing to the sea. Nitrogen compounds in particular tend to accumulate in groundwater.

Dead zones can also linger if there is a dearth of nearby healthy populations of marine plants and animals that can provide the "seed stock" from which the missing communities can be restored. Indeed, the flora and fauna that once lived in the affected area may even have gone extinct. It is possible for native marine animals to drift large distances as larvae from healthy ecosystems and to eventually reestablish themselves in a suitable vacant biological niche. Sometimes, however, these would-be returnee species find themselves supplanted by opportunistic invading organisms that have taken up all suitable habitats.

Finally, eutrophication often causes alterations in ecosystem composition that are not easily reversed [*see illustration on opposite page*]. As nutrient concentrations begin to climb early on, some species decline, but ecosystems as a whole may remain strong for a long while if the natural populations can withstand a relatively high amount of phytoplankton growth and the like. At some point, however, a threshold is reached at which the loss of key species yields an abrupt collapse to a new degraded state. This new equilibrium arises from the presence of some remaining species that are tolerant of eutrophication's effects and from the arrival of opportunistic creatures from elsewhere. Unfortunately, the new state is often quite stable. Consequently, simply cutting back the nutrient supply to its pre-eutrophication levels may not restore the original ecosystem; lowering nutrient concentrations to levels much below their starting points may be required.

To further complicate matters, the threshold for change from a natural state to a degraded one typically comes earlier if an ecosystem's resilience is diminished by overfishing. Therefore, it may also be necessary to reduce fishing activities markedly before the healthy state can return. If the species of the original system have been lost or invaders have appeared, the former pristine conditions may never be regained.

Eliminating Dead Zones

KNOWING WHAT TO DO to fix dead zones will not be enough; a key to reviving them is for governments to believe it is an important goal and to take the lead. Indeed, scientists have documented few cases of dead zone recovery, because reducing nutrient runoff from the land requires major changes in agricultural practices and wastewater treatment efforts. Most such programs have so far achieved only partial cuts in terrestrial nutrient outflows.

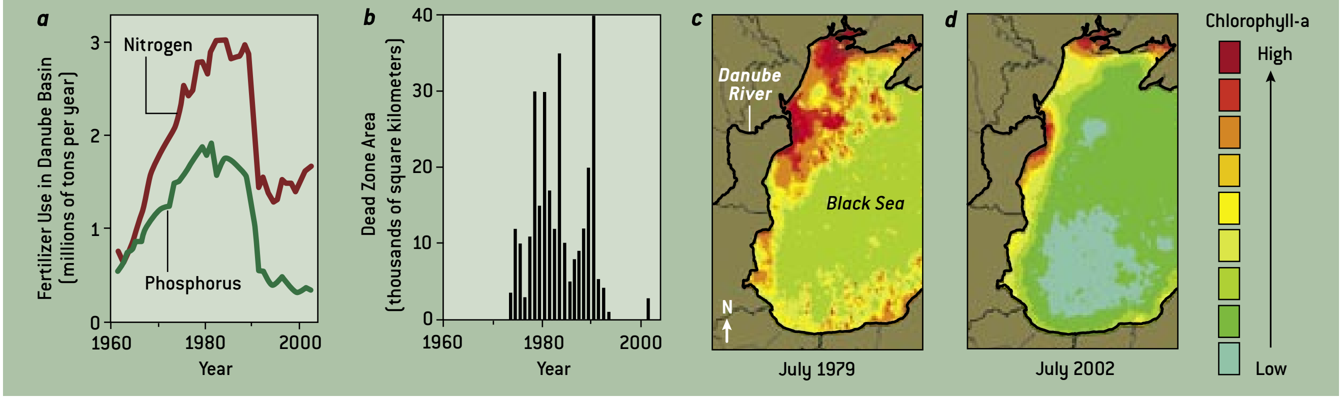
To shrink nutrient loads, comprehensive plans (at the scale of an entire river catchment system) must be put in place that keep nitrogen and phosphorus on the land and out of the water. Such efforts are currently under way in the Chesapeake Bay and in the Black Sea. In the latter case, surrounding governments, aided by the United Nations Global Environment Facility, have agreed to pursue a landmark initiative to maintain nutrient runoff levels at those of the mid-1990s, a scheme that seems to be aiding recovery through pilot-scale projects to improve farming practices and waste treatment.

Two serious problems must be over-

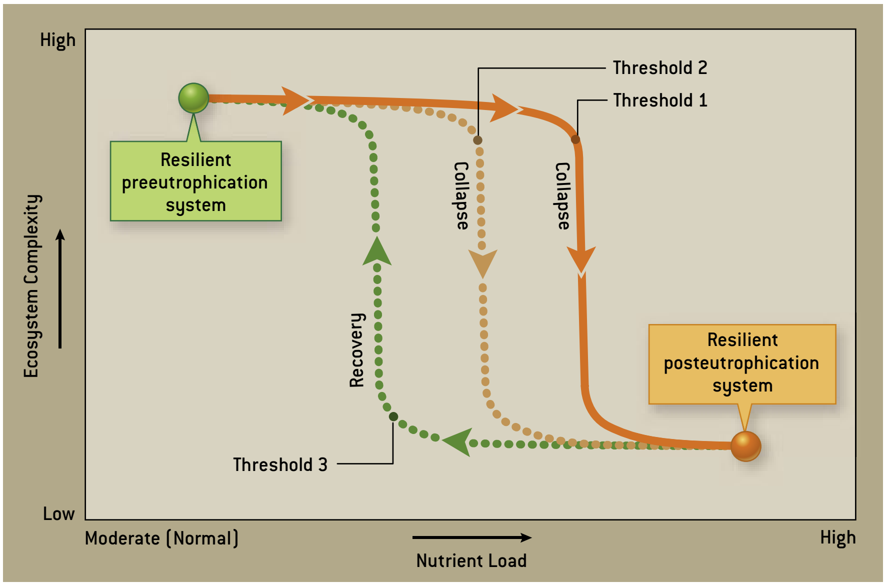
The Black Sea Comes Back

The recovery of the Black Sea dead zone underscores the need to reduce agricultural, sewage and other nutrient runoff from the land if affected areas are to be restored to health. The dead zone adjacent to the northwest coast of the Black Sea began to revive only after the communist system collapsed in 1989, which prevented the continuation of intensive farming—including large-scale raising of livestock and heavy application of fertilizers containing nitrogen and phosphorus (*a*)—that had been in place since the 1960s. Nutrient residues made their way into the Danube River and other watersheds and eventually down into the Black Sea, which caused the dead zone to appear in 1973 and to return in the summer for the next 21 years (*b*). Red color in a satellite image from 1979 (*c*), for instance, clearly reveals a large expanse of overfertilized water. (In that image and in *d*, eutrophication was assessed by determining the concentrations of chlorophyll-a, an indicator of plant growth, in surface waters.)

Within five years after the intensive farming ended, the degraded region had returned to life (*b* and *d*), relapsing only during the exceptionally hot summer of 2001. By 2002 mussel communities in the area had reestablished themselves. The sea may again be at risk, however, as central European economies recover and agriculture there begins to intensify again.



CZCS/SeaWiFS DATA PROCESSED BY ABIGAIL McQUATTERS-GOLLOP (c and d)



REDUCING NUTRIENT LEVELS to those present before a dead zone has formed may not be enough to ensure recovery, as shown in this graph, which relates the health of an ecosystem (in terms of complexity, or species diversity) and the amount of nutrients with which it must contend. A system with high complexity and moderate terrestrial nutrient inflows tends to be highly resilient until the nutrient load finally surpasses some level (*threshold 1*), causing the system to collapse to a much less complex state. This breaking point arrives earlier (*threshold 2*) if overfishing has depleted the numbers of top predator fish, which reduces species diversity. Unfortunately, the new degraded state is also typically resistant to change and may recover its lost complexity only when nutrient influxes drop significantly below the starting levels (*threshold 3*). Even then, an ecosystem may never return to its previous state if key species have gone extinct.

JEN CHRISTIANSEN

come, however, before full and sustainable recovery of the Black Sea ecosystem can occur. European authorities have to take steps to ensure that renewed economic development does not lead to the resurgence of terrestrial nutrient release to the sea. They should, for instance, invest in major waste-reduction projects that employ the latest technology. This point is particularly important for the Danube basin, where six of the countries have joined or are in the process of joining the European Union. Some farmers from western Europe, where intensive agricultural practices have often caused eutrophic rivers and coastal waters, are eager to buy up central European farmland.

Next governments must reduce the intensity of commercial fishing activities enough to allow depleted stocks of piscine predators to recover. In addition, the trawls and dredges on fishing boats destroy key benthic communities and must be regulated more effectively.

In fact, maritime nations worldwide must work to lessen fishing pressure on eutrophic areas, difficult as that is to achieve with more than half the planet's fisheries being overexploited today. Although an international agreement has been reached to establish by 2012 a global network of marine protected areas—which would help curb overfishing and save the vital seed stock needed for dead zone recovery—the agreement's goals are unlikely to be met, because enforcement mechanisms are lacking.

Even if a eutrophic ecosystem makes a partial comeback, authorities must be aware that a partial recovery may leave it in a highly unstable situation. Mussels, for example, have an extraordinary capacity for filtering water, and the establishment of mussel beds on artificial reefs has been employed to improve water quality. But bacterial decomposition of mussel excreta and dead individuals consumes large amounts of oxygen, which can result in boom-and-bust cycles in locations where water mixing is poor and oxygen replenishment is limited. In these cases, thriving mussel communities suddenly collapse, leaving a dead zone until the organic material has fully decayed and recovery begins again. Scientists have observed this phenomenon in Baltic Sea estuaries. The challenge for marine resource managers is to maintain conditions that sustain resilient and diverse systems—even where full recovery is no longer possible.

On a more subtle level, the entire concept of rating the health or quality of an ecosystem depends on the values of local inhabitants. For some, the desirable outcome of remedial action might be a sea of small prey fish; for others, only restoration of a sea filled with apex predators will be acceptable.

Coastal dead zones remind us that humanity cannot simply expect natural ecosystems to absorb our wastes without severe and often unexpected consequences. We now know how to revive dead zones, but ultimately the steps required to do so depend on our recognition of the ramifications to the environment of waste disposal and the degree to which we value the world's marine ecosystems. SA

MORE TO EXPLORE

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