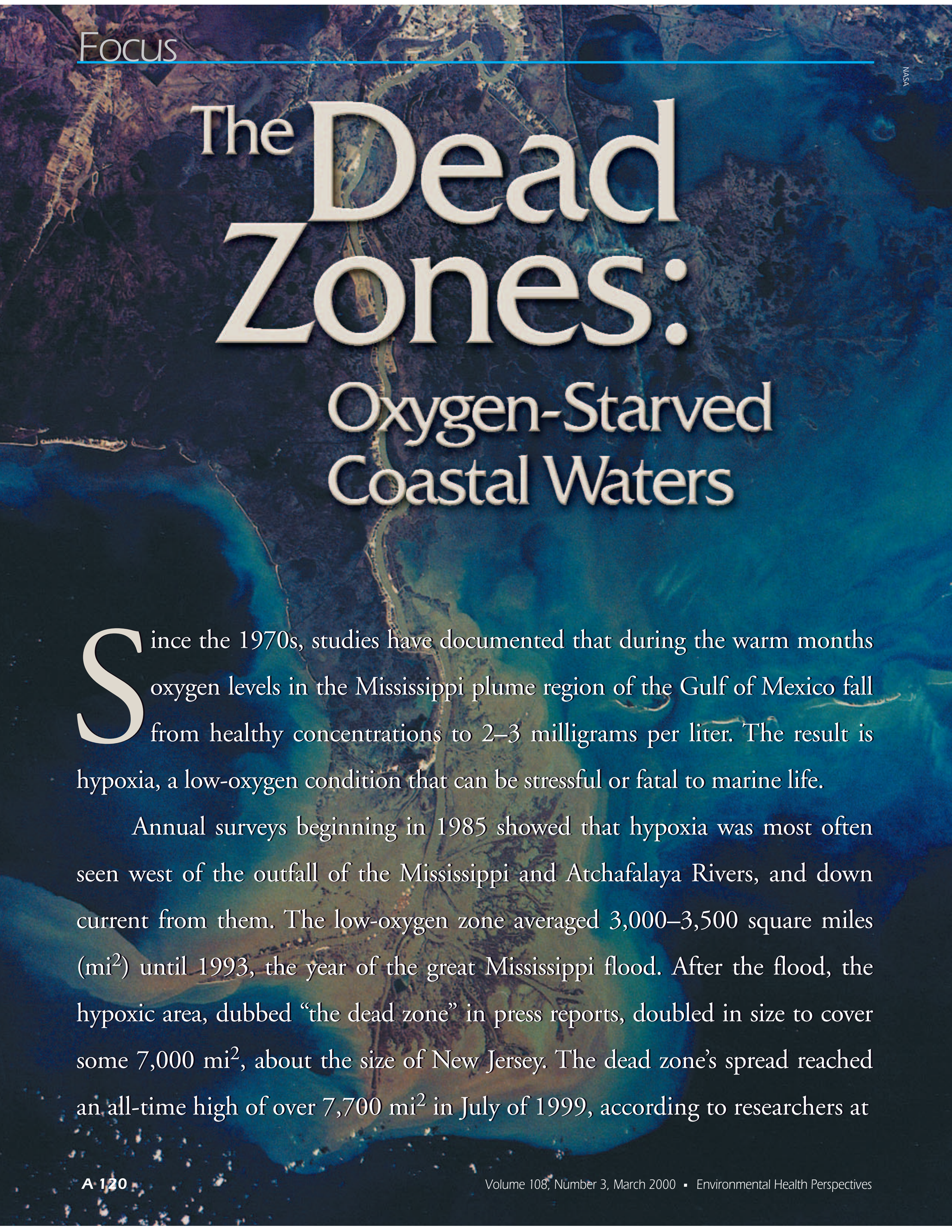


NASA

The Dead Zones:

Oxygen-Starved Coastal Waters

Since the 1970s, studies have documented that during the warm months oxygen levels in the Mississippi plume region of the Gulf of Mexico fall from healthy concentrations to 2–3 milligrams per liter. The result is hypoxia, a low-oxygen condition that can be stressful or fatal to marine life.

Annual surveys beginning in 1985 showed that hypoxia was most often seen west of the outfall of the Mississippi and Atchafalaya Rivers, and down current from them. The low-oxygen zone averaged 3,000–3,500 square miles (mi^2) until 1993, the year of the great Mississippi flood. After the flood, the hypoxic area, dubbed “the dead zone” in press reports, doubled in size to cover some 7,000 mi^2, about the size of New Jersey. The dead zone’s spread reached an all-time high of over 7,700 mi^2 in July of 1999, according to researchers at the Louisiana Universities Marine Consortium.

Scientists attribute the Gulf of Mexico hypoxic zone largely to nutrient runoff (particularly nitrogen) from agriculture in the enormous Mississippi basin, which releases 1.6 million metric tons of nitrogen annually, according to the *Integrated Assessment of Hypoxia in the Northern Gulf of Mexico*, a draft summary of six reports on various aspects of hypoxia in the Gulf of Mexico commissioned by the White House Committee on Environment and Natural Resources (CENR). During the warm months, these nutrients fuel eutrophication, which causes excessive algal blooms that can degrade aquatic habitats by reducing light levels, destroying habitats (including fragile systems such as coral reefs), and harming marine life by producing toxins, some of which also harm humans. Algae form the base of the food chain, but when they bloom in excess, their decay in eutrophic waters can promote hypoxia.

Although the Gulf of Mexico hypoxic zone is the largest anthropogenic dead zone in the Western Hemisphere, it is only one of many. Reports of hypoxic events have been increasing since the mid-1960s. Worldwide, dead zones exist in areas such as Japan's Seto Island Sea and its harbors, the northern Adriatic Sea, the Baltic Sea (with over 38,000 mi^2 of hypoxic water, about 33% of the sea), the Black Sea (90% hypoxic), and many others. Marine ecosystems are complex and incompletely understood, and human activities cannot always be named as direct causes of hypoxia. However, problems in dead zones such as in the Gulf of Mexico parallel a global decline in water quality associated with increasing human populations and coastal development, and scientists generally concur that eutrophication and hypoxia should be taken very seriously. A June 1999 report from the National Academy of Sciences' Council for Agricultural Science and Technology, *Gulf of Mexico Hypoxia: Land and Sea Interactions*, states that hypoxic zones "are now one of the most widespread, accelerating, human-induced deleterious impacts in the world's marine environments."

In 1998, following a request by the U.S. Environmental Protection Agency (EPA), the CENR commissioned its series of six reports summarizing the scientific knowledge, environmental and ecological consequences, and possible remedies for hypoxia in the Gulf of Mexico. The six reports, issued in spring 1999, show that in the Mississippi, as in other U.S. and international coastal regions, human activities have caused ecosystem changes that may affect human, economic, and environmental health in the short and long term. Reversing these changes will require a long-term commitment both to reducing nutrient inputs and to conducting basic research to improve understanding of coastal ecosystems and how human activities affect them.

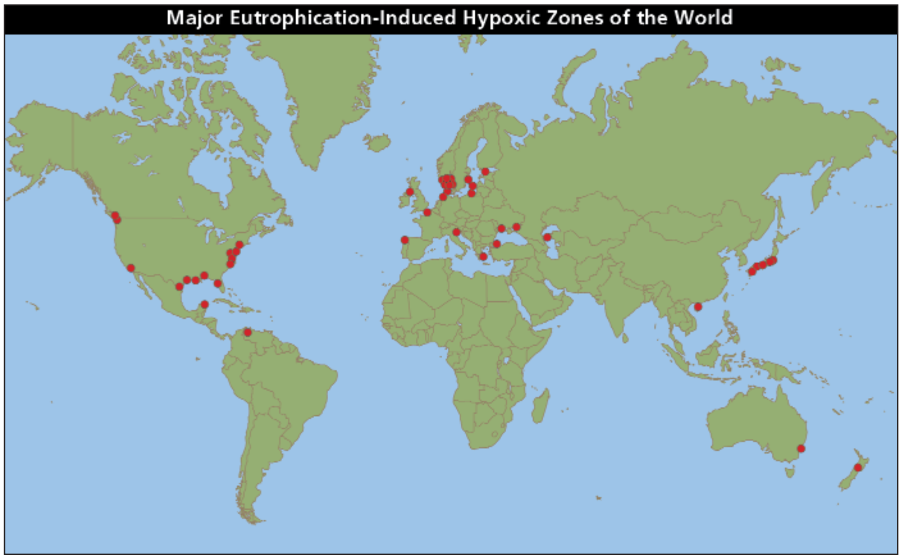
The Causes and Consequences of Hypoxia

Hypoxia and even anoxia—a total loss of oxygen—occur naturally in many of the world's ocean basins and seas and also along some coastlines. Periodic anoxia occurs in one-third of U.S. estuaries and hypoxia occurs in half, particularly in the Gulf of Mexico and the mid-Atlantic. Troughs in the Chesapeake Bay and the rippling floor of the Long Island Sound are also prone to hypoxia. Periodic and seasonal cycles of enhanced algal growth occur naturally when warm temperatures and adequate nutrients are present, and can contribute to hypoxia. Overall, however, the widespread global increase of eutrophication and hypoxia points to human causes.

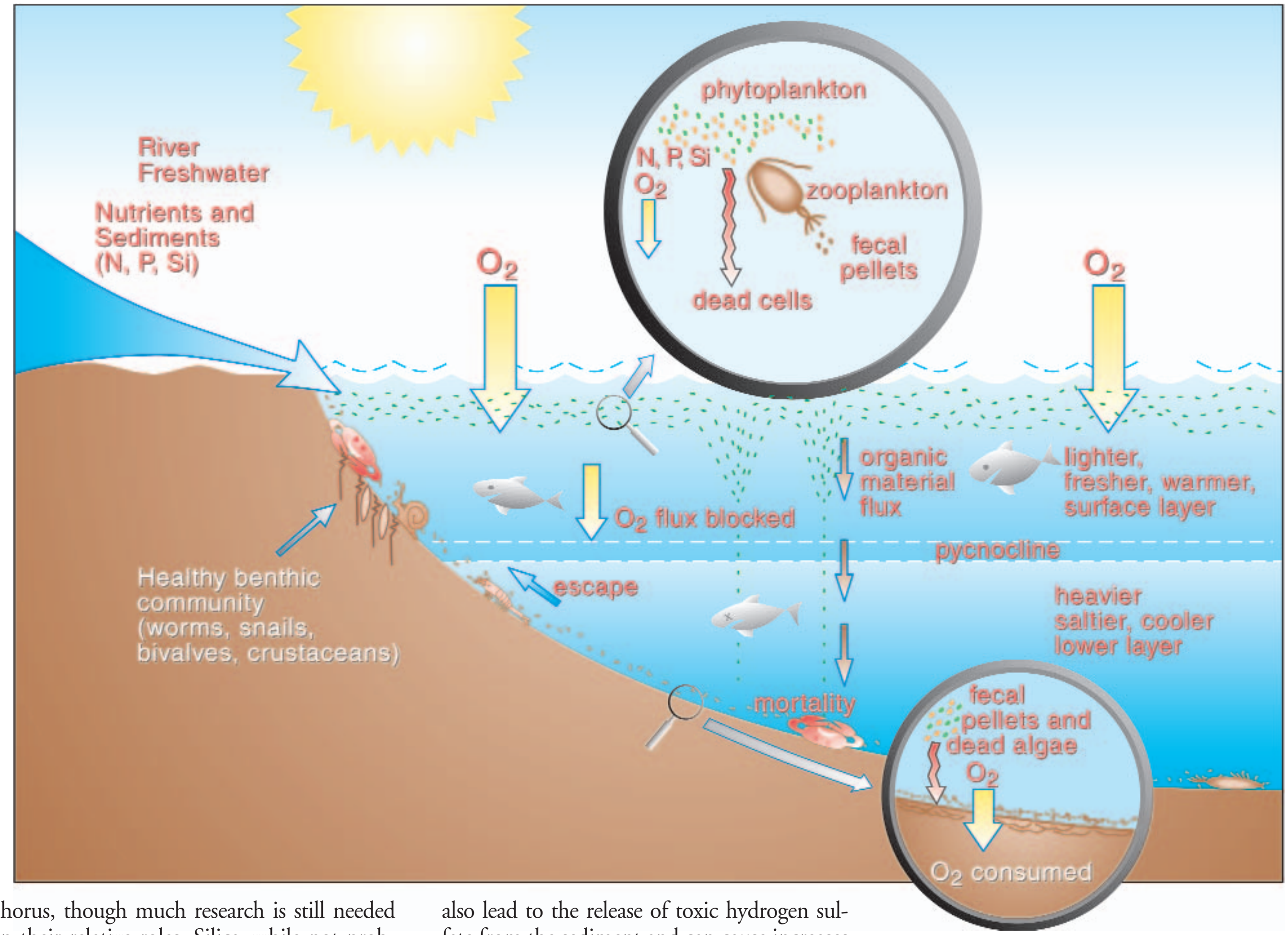
Most programs seeking to reduce coastal eutrophication and hypoxia target sources of nitrogen because nitrogen concentrations control phytoplankton growth in saltwater. Nitrogen is essential to most living organisms, and in a fixed form (combined with other elements) it controls the productivity and species composition—the type and proportion of algae in a given area—of many ecosystems. But human additions of fixed nitrogen have vastly altered the nitrogen cycle. In an article in the 25 July 1997 issue of *Science*, Peter Vitousek and colleagues stated that anthropogenic changes to the nitrogen cycle have doubled relative to similar changes to the carbon cycle. Anthropogenic inputs add as much as 190 metric tons of fixed nitrogen per year to terrestrial systems, Vitousek says. While agriculture is the main source for much of the nitrogen, water quality problems in other areas may stem from a variety of human activities including land transformation, groundwater drainage, urban stormwater runoff, sewage treatment, or atmospheric emissions through fossil fuel burning and volatilization of agricultural waste. "It's as if we've taken these already-hypoxia-prone systems and pushed them over the edge," says Danielle Luttenberg, coordinator of the Harmful Algal Bloom Monitoring and Assessment Program at the U.S. National Oceanic and Atmospheric Administration (NOAA).

Hypoxia is part of a series of ecosystem responses to declines in water quality. It generally affects enclosed water bodies such as lakes, bays, estuaries, and seas, where local conditions including bottom topography, wind and wave patterns, and inflow from large rivers promote stratification, the separation of oxygen-rich upper layers of water from the lower, less-oxygenated layers. Hypoxia changes the energy flow of marine systems, altering the dynamics of the food chain, says Robert J. Diaz, a professor of marine science at the College of William and Mary in Williamsburg, Virginia, who specializes in the effects of hypoxia. "In nonhypoxic conditions, sun and nutrients support the growth of phytoplankton, which can be considered the base of the food chain for many fish and invertebrate species," Diaz says. "The portion of phytoplankton . . . that settles to the bottom through the water column [a vertical cross-section of water from surface to bottom] is the energy for a basic food chain of worms to shrimp, crabs, and bottom-feeding fish. When too much [phytoplankton] gets to the bottom, the invertebrates can't handle the excess food, which leads to bacterial blooms and to oxygen depletion if bottom waters are stratified." When excess nutrients reach stratified water, a progression of responses results, starting with eutrophication. The primary nutrients of concern are nitrogen and phos-

Major Eutrophication-Induced Hypoxic Zones of the World



Source: Downing JA, et al. Gulf of Mexico hypoxia: land and sea interactions. Task force report no. 134. Ames, IA:Council for Agricultural Science and Technology, 1999;6.



How hypoxia happens. Hypoxic zones arise when nutrients fuel excess production of primary marine organisms. These organisms fall to the ocean bottom and decompose, consuming oxygen that cannot be renewed from surface waters because of stratification of fresh- and saltwater. Oxygen consumption decreases dissolved oxygen levels to below the concentrations needed to sustain marine life.

Source: Downing JA, et al. Gulf of Mexico hypoxia: land and sea interactions. Task force report no. 134. Ames, IA:Council for Agricultural Science and Technology, 1999;5.

phorus, though much research is still needed on their relative roles. Silica, while not problematic for enhancing eutrophication, may alter species composition.

Biological response to hypoxia varies according to species tolerance and the degree and frequency of the hypoxic event, but as its freqency increases, hypoxia tends to reduce biomass and diversity of benthic, or bottom-dwelling, communities. In a 1995 book on the effects of benthic hypoxia titled *Oceanography and Marine Biology: An Annual Review*, Diaz and Rutger Rosenberg reported that aperiodic and short-term seasonal hypoxia can cause mass mortality of benthic fauna that cannot escape the affected region. As hypoxia becomes more persistent, benthic communities tend to become smaller and less diverse, shifting to disturbance-adapted, shorter-lived invertebrate species that can withstand lower oxygen concentrations, and those that can adapt to periods of "pulsed" injection of nutrients.

Diaz adds that bacterial decomposition and low dissolved oxygen alter normal sediment geochemistry, releasing phosphates and nitrates from the sediment and making them available to phytoplankton—which leads to more organic production, perpetuating the hypoxic system. "Low-oxygen conditions can also lead to the release of toxic hydrogen sulfate from the sediment and can cause increases in aquatic carbon dioxide and changes in pH levels, adding to the stress of any organism that cannot escape," Diaz says.

Hypoxia-related changes in benthic communities can affect marine life in diverse waters. In the Black Sea, hypoxia led to the collapse of the benthos and mass mortality of valuable demersal (bottom-dwelling) fish such as turbot and flounder. The present Black Sea catch consists of smaller, less valuable fish such as anchovy, horse mackerel, and sprat. Hypoxia in the Kattegat (a branch of the Baltic Sea between Denmark and Sweden) eliminated Norwegian lobster fishing, and it has reduced or stressed many other fisheries including the Seto Island Sea, the Baltic Sea, the Adriatic Sea, and the Sea of Azov. Worsening hypoxia could affect the abundant Gulf of Mexico fisheries, whose harvest of fish and shellfish is worth over $2.8 billion annually, according to the most recent (1996) statistics from the National Marine Fisheries Service.

Declines in U.S. fishery production have been forecast but have not yet occurred. However, the *Integrated National Assessment of Hypoxia and Eutrophication*, which was developed by NOAA for the CENR's Task Force on Harmful Algal Blooms and Hypoxia, found that a majority of U.S. estuaries show signs of moderate to serious water quality degradation. According to the report, symptoms of primary eutrophication occurred in 58 of 139 estuaries assessed. These symptoms include increased chlorophyll production, growth of algae on submerged aquatic vegetation (an important marine habitat, nursery, and food source), and the proliferation of macroalgae, or seaweed, that can take over and degrade delicate systems such as coral reefs.

Secondary symptoms of eutrophication, according to the assessment, are low dissolved oxygen, loss of submerged aquatic vegetation, and development of nuisance algal blooms. Eighty-two of the estuaries had at least one symptom of secondary eutrophication. Historic trends from 1970 to 1995 show that worsening conditions outnumber improvements, the report says.

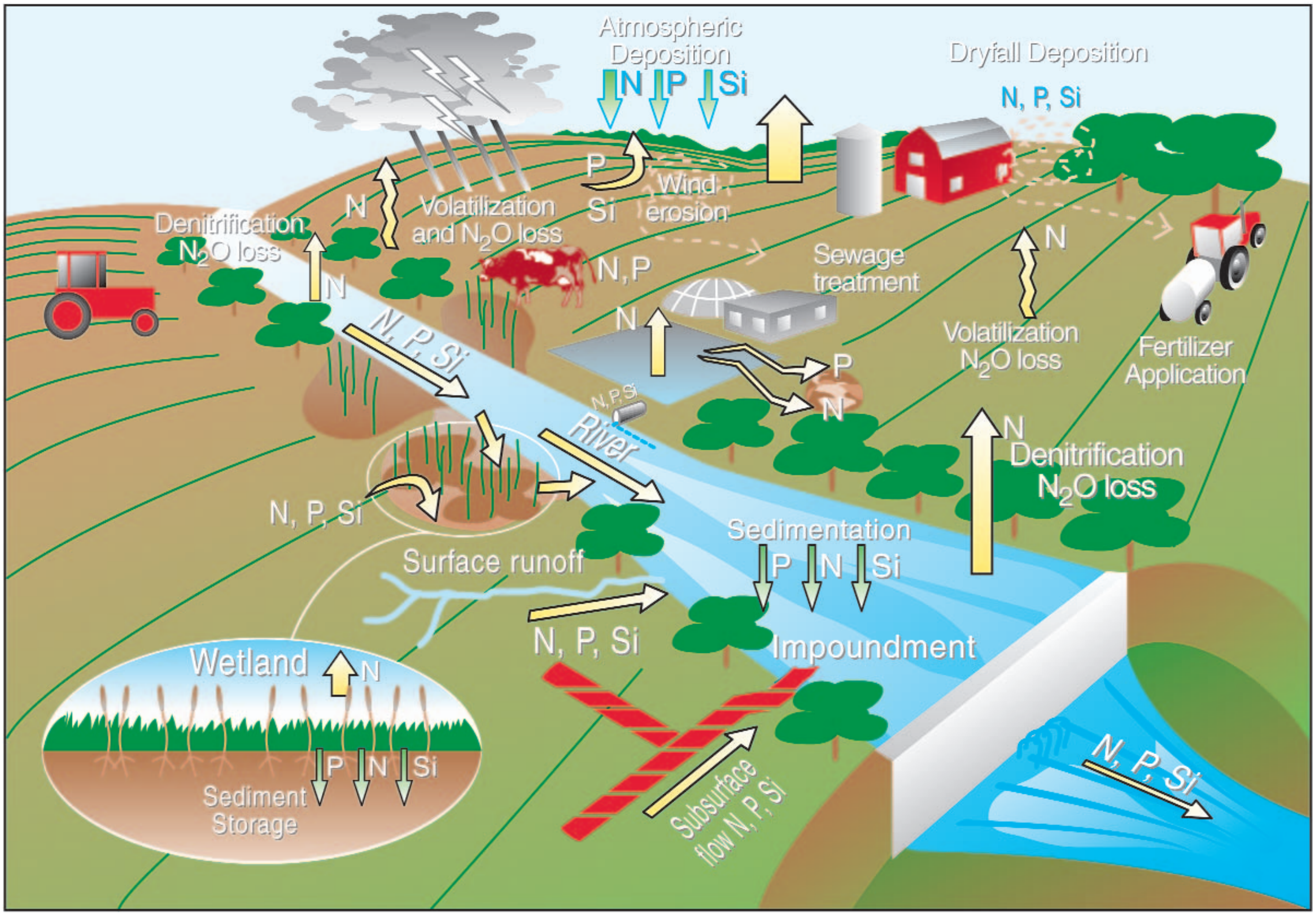
Other Causes: Algal Blooms and Climate

Anthropogenic nutrient loading is also believed to be contributing to the global increase in the frequency, size, and duration of harmful algal blooms, known as HABs, which can alter the function of coastal ecosystems or potentially threaten human health. Such blooms have caused large-scale deaths in both wild and farmed stocks of economically important seafood species. In 1986 and 1989, the golden-brown algae *Heterosigma akashiwo* killed a total of $10.5 million worth of farmed salmon along the western U.S. and Canadian coast. According to NOAA's *Integrated Report on Harmful Algal Blooms*, HAB outbreaks have increased globally in scope, duration, and economic costs—though increased reporting may be due to better monitoring, the report says.

Many species that cause HABs (such as the "red tides" caused by the toxin-producing dinoflagellates *Alexandrium* spp. and *Gymnodinium breve*, both of which periodically trigger shellfishery closures in the U.S. northeast and southeast) are not associated with polluted water but are current-borne. They exist naturally in certain marine areas, and they have been around for a long time. "The red tide was noted by the Spaniards when they were exploring Florida," says Luttenberg. "But some species do respond to nutrient levels. Harmful cyanobacteria [blue-green algae, which bloom in fresh or low-saline water] are pretty clearly related to nutrients. And research from all over the world indicates a relationship between macroalgae and nutrients. Some HABs may respond to changes in nutrient levels, or they may respond to nutrient ratios."

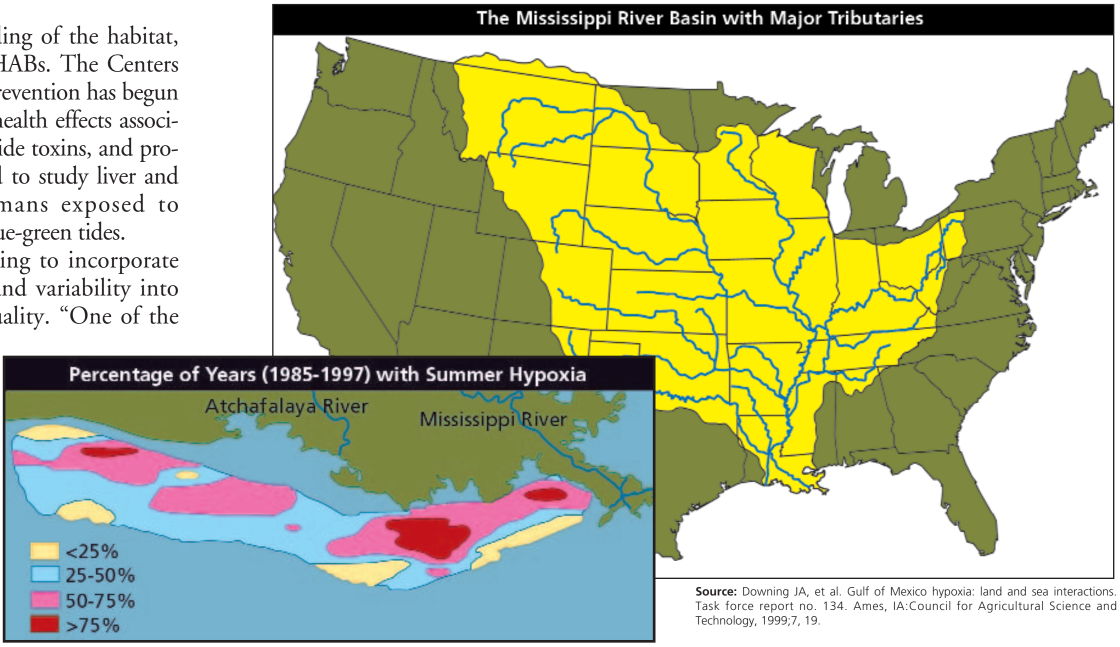
Research by teams led by R. Eugene Turner of Louisiana State University's Coastal Ecology Institute in Baton Rouge and Nancy N. Rabalais of the Louisiana Universities Marine Consortium also suggests that changes in the relative concentrations of nitrogen, silica, and phosphorus, especially a decrease in silica relative to nitrogen, may be causing a change in algal community composition. "As the ratio changes, there are shifts in the types of phytoplankton produced," Rabalais says. In a June 1996 paper in the journal *Estuaries*, Rabalais and colleagues documented the appearance of phytoplankton species not found in pre-1950 sediments. These include *Dinophysis caudata*, a dinoflagellate associated with diarrheic shellfish poisoning, and *Pseudo-nitzschia*, a species usually found in the waters off the U.S. west coast. Some varieties of *Pseudo-nitzschia* emit a toxin called domoic acid that accumulates in the tissues of fish and shellfish and can cause permanent amnesia in people and animals who eat contaminated seafood.

States affected by HABs routinely monitor for outbreaks of algal blooms, following guidelines set by the U.S. Food and Drug Administration. Little is known about the role of toxic algae in their habitats or about their effects on animals and humans, but state and federal agencies are supporting studies aimed



The flow to the sea. Three major nutrients, nitrogen (N), phosphorus (P), and silicon (Si), are released from agricultural landscapes by wind erosion, volatilization, loss from soil, and sewage and waste treatment. Rain and dust, as well as runoff and subsurface flow, deposit these nutrients into waterways and onto land. Nutrients may also be trapped in wetlands and lakes.

Source: Downing JA, et al. Gulf of Mexico hypoxia: land and sea interactions. Task force report no. 134. Ames, IA:Council for Agricultural Science and Technology, 1999;24.



Source: Downing JA, et al. Gulf of Mexico hypoxia: land and sea interactions. Task force report no. 134. Ames, IA:Council for Agricultural Science and Technology, 1999;7, 19.

at broadening understanding of the habitat, biology, and ecology of HABs. The Centers for Disease Control and Prevention has begun studies of the respiratory health effects associated with aerosolized red tide toxins, and protocols are being developed to study liver and kidney damage in humans exposed to cyanobacterial toxins in blue-green tides.

Scientists are also trying to incorporate data on climate change and variability into questions about water quality. "One of the key questions in water quality is how to tease apart human effects and the effects of hurricanes," says Hans Paerl, Kenan professor of marine and environmental sciences at the University of North Carolina at Chapel Hill's Institute of Marine Sciences in Morehead City. Excessive algal growth and blooms responding to increased nutrient loading is a serious water quality problem in the Neuse River estuary, which opens into North Carolina's Pamlico Sound, a major fisheries nursery for the mid-Atlantic. "The Neuse estuary is affected by nutrient loading from agricultural, urban, and industrial sources, and conversion of upstream and coastal wetlands to housing and other development. Nitrogen loading to the estuary has increased by at least 30% over the past 20 years," Paerl says.

The combination of eutrophication and vertical salinity stratification (in which low-density freshwater overlays higher-density saltwater but does not mix with it, turning the lower layer into a so-called salt wedge) makes the Neuse estuary prone to hypoxia. Also, the islands of the Outer Banks partially enclose the greater Pamlico Sound, greatly reducing water and nutrient exchange with the coastal ocean. As a result, nutrient inputs entering the sound can remain there for at least a year, Paerl explains. Blooms of dinoflagellates, cryptomonads (a type of biflagellate algae), and blue-green algae commonly appear in the upper estuary. Paerl and his colleagues will monitor the Neuse/Pamlico system closely to observe effects on algal growth and fish following the three hurricanes—Dennis, Floyd, and Irene—that struck the North Carolina coast between September and October 1999. "We've had a 200–500-year flood event and have never seen anything approaching this magnitude," Paerl says.

A week after Hurricane Floyd struck, nutrient-laden freshwater from the Neuse, Tar, and Pamlico Rivers sent coffee-colored plumes deep into the blue-gray water of the sound, and salinity dipped to 30–50% of normal levels. Chlorophyll levels doubled, and a week later, hypoxia appeared throughout the estuaries and in parts of the sound. Then came Irene. "Hurricane Irene remixed Pamlico Sound, but the nutrients are still there because the Outer Banks prevents their expulsion to the coastal ocean," says Paerl. "We think there's a high potential for algal blooms if we have a hot, calm spring and summer in 2000. We should be prepared for unusual biological events that may at least temporarily impair water quality and fisheries habitat."

Case Study: Hypoxia in the Gulf of Mexico

The Gulf of Mexico hypoxia problem demonstrates the often conflicting interaction between human productivity and ecosystem health. In the course of its nearly 4,000-mile journey to the Gulf of Mexico, the Mississippi River enfolds the flow of many large rivers—the Ohio, the Arkansas, the Missouri, the Illinois, and the Tennessee—along with their innumerable small and large tributaries. The Mississippi basin is hugely important economically; it drains 31 states and 40% of the contiguous United States. The basin represents 55% of American agricultural lands and 33% of U.S. farm-related jobs, and produces over $98 billion annually in agriculture, according to *Gulf of Mexico Hypoxia*.

However, productivity in the Mississippi basin has been ecologically costly. The Mississippi's flow has been extensively altered since the mid-1800s through elimination of wetlands (which can help control nutrient runoff), construction of navigation and flood control levees, and annexation of the Atchafalaya River for flood control. Riverine nutrient loads from agriculture have increased two- to threefold since the 1950s. Since 1980, the Mississippi and Atchafalaya Rivers have annually discharged 1.6 million metric tons of nitrogen (mostly nitrate), 100,000 metric tons of phosphorus, and 200,000 metric tons of silica into the basin, according to the *Integrated Assessment of Hypoxia in the Northern Gulf of Mexico*. The report adds that about 56% of the nitrate enters the Mississippi above the Ohio river, in the six states where agricultural production is highest, and that eutrophication has impaired water quality throughout the basin.

The waters of the Mississippi and Atchafalaya Rivers provide 60% of the freshwater input to the Gulf of Mexico. When they reach the gulf, the waters form a broad, nutrient-rich, stratified plume that supports algal blooms along the continental shelf, extending from Louisiana to eastern Texas. Beginning in late spring, hypoxia appears across the shelf, generally at depths of 5–30 meters. Unless winds or tropical storms mix the water, hypoxia and anoxia may persist for weeks to months from May to September. During hypoxic periods, the abundance and biomass of fish and shrimp in the hypoxic zone diminishes, causing commercial shrimping to shift to nonhypoxic zones. However, according to the second of the six CENR reports, *Topic 2: Ecological and Economic Consequences of Hypoxia*, statistical reductions in overall catches were not measured (though the report states that reductions may have occurred).

Like many U.S. coastal ecosystems, the Gulf of Mexico was not monitored until water quality degradation was advanced. The first documentation of hypoxia in the Gulf of Mexico occurred during the 1970s in connection with environmental assessments of oil production and studies of transportation in the gulf. Routine data gathering on the extent and effects of hypoxia in the gulf began in 1985, led by Turner and Rabalais. Sampling during annual five-day cruises documented and mapped the presence of hypoxia in the gulf, though Rabalais cautions that the maps made during the surveillance cruises should be seen as incomplete snapshots. “What these maps show is only a five-day picture of the whole process,” she says.

Research by Turner, Rabalais, and others has shown correlations between increased fertilizer use and productivity and oxygen depletion in the Gulf of Mexico. In the absence of long-term data on riverine nutrient and oxygen concentrations, research teams analyzed sediment cores extracted from the bed in the coastal shelf, which represented organic deposition from 1904 through recent years. Analysis of organic matter buried in the sediments showed that eutrophication and increased organic production began to grow in the 1940s, in parallel with increasing use of agricultural fertilizers. In a series of papers, Turner, Rabalais, and other researchers showed a decline in benthic foraminifera and ostracods (shelled organisms that require highly oxygenated waters), also coincident with increased fertilizer use, indicating increasing oxygen stress in the gulf beginning in the 1950s and accelerating in the 1980s.

The Way to Cleaner Water

Scientists contributing to the six CENR reports concur that water quality and hypoxia could worsen even if nutrient inputs do not increase because of other factors including weather patterns, temperature, and precipitation in the gulf and the drainage basin. The remediation options outlined in the *Integrated Report on Harmful Algal Blooms* are to reduce nitrogen inputs to streams and rivers in the Mississippi basin and to restore and enhance naturally occurring denitrification (nitrogen removal) rates in the basin.

However, it’s difficult to know precisely what level of cleanup to aim for in the gulf, or indeed, in U.S. waters in general. Like the Gulf of Mexico, many other bodies such as Pamlico Sound have been monitored little or not at all, despite their economic significance. “When we notice [problems with hypoxia], systems have already been altered to a significant degree,” Diaz says. “By the time you have drastic changes in aquatic communities and fish mortality, these systems are altered. We don’t know what prehypoxic levels were in the gulf.”

Yet experience with hypoxia in other countries has demonstrated not only the potential consequences of prolonged water quality degradation but also the potential for recovery. Multinational efforts are under way to address water quality problems affecting the Baltic Sea and the Danube River delta. In the Seto Island Sea, efforts to halve nutrient runoff appear to be slowly reducing eutrophication levels.

Governments and citizens groups have launched a number of extensive programs to reduce eutrophication and hypoxia caused by various human activities in a number of U.S. water bodies. A multi-state, multi-stakeholder campaign begun in 1987 on behalf of the Chesapeake Bay sought to reduce overall nitrogen and phosphorus loading from point sources such as wastewater treatment and nonpoint sources such as transportation and agriculture by 40% by this year (this goal has not yet been met, however). In the highly urbanized Long Island Sound, where hypoxia, declining water quality, and algal blooms threaten marine resources potentially worth $4.9 billion (in terms of jobs, commercial fishing and processing, and recreational boating, fishing, and swimming), studies showed that the major nitrogen contributor was partially treated sewage. With the cooperation of the EPA, state and local governments and major wastewater treatment companies in Connecticut and New York (the states bordering the sound) are upgrading their plants to help meet a goal of 58% reduction in point source nutrient deposition.

Many researchers look to the Chesapeake Bay’s basin management program as a model for addressing water quality. Though there has been no significant change in overall water quality in the bay—algal blooms and hypoxia still occur, and strategies to address inputs from agriculture, power plants, and auto emissions have not reduced nutrient loads as expected—conditions have improved in several contributing rivers where nutrient loading was diminished, and there has been a modest recovery of sea grass growth.

Donald Boesch, a biological oceanographer with the University of Maryland Center for Environmental Science in Cambridge, calls the Chesapeake program a “qualified success, in that degradation has stopped and is, to a certain extent, being reversed.” But he notes that a strong feeling of ownership on the part of the public was a major factor in the bay’s improvement. “People just do not like the idea of ‘their bay’ being polluted,” he says. “The Gulf of Mexico is very different. Few people live there; they can’t call it ‘my coast.’ The states [working on the Chesapeake Bay] have a vested interest; for the Mississippi, it’s very different. Most of the agricultural sources [of nutrient loading] are 1,000–1,500 miles away.”

Elsewhere in the United States, programs targeting specific nutrient loading sources have begun to show results. Chlorophyll levels in Long Island Sound appear to be diminishing with improvements in sewage treatment, and in Tampa Bay, reductions in nutrient loads have begun to result in improved water clarity, reduced cyanobacterial bloom, increases in sea grass growth, and rising catches of valuable fish, such as speckled trout, that depend on the sea grasses. In North Carolina, says Paerl, well-defined nutrient cutbacks, including a legislatively mandated 30% reduction in nitrogen inputs into the Neuse River basin, have been formulated to reduce hypoxic effects.

There appears to be strong federal support for reversing coastal hypoxia. The issue is being addressed through a number of laws including the Clean Water Act, the Clean Air Act, and the Harmful Algal Bloom and Hypoxia Research Control Act of 1998. As part of the Clean Water Initiative, President Bill Clinton set aside $5 billion, including $322 million for the Gulf of Mexico, for projects to clean up America’s waterways. To address the basin management concept in the Mississippi basin, the EPA has divided the watershed into six sub-basins and has begun developing strategies for addressing water quality in each. The EPA is also developing nutrient assessment criteria based on water quality indicators (such as chlorophyll, turbidity, and total nitrogen) for three water body types (lakes/reservoirs, streams/rivers, and estuaries/coastlines), to be completed by 2003. NOAA, the EPA, and other federal agencies are supporting and collaborating on research to expand understanding of hypoxia and the causes and controls of eutrophication in terms of climatic, physical, and chemical factors and human interactions with the environment.

In the conclusion of the first of the six CENR reports, *Topic 1: Characterization of Hypoxia*, Rabalais and her coauthors urge multi-level, multi-institutional support as a way of implementing nutrient reduction programs. The report notes that, just as declines in water quality increased over many years, recovery in the Gulf of Mexico and other systems will take many years. “The science of cultural eutrophication is past its infancy but the science of restoration of enriched systems is not,” states the report. The authors go on to stress that for recovery strategies to remain effective, they must be accompanied by a long-term commitment to continuing research, including continued examination of existing data such as hydrogeographic, chemical, and biological conditions and events in the gulf; improved surveying to better quantify the problem; and continued monitoring. The research, like the recovery of the gulf, may take decades, but both are necessary to the continued recovery of degradation resulting from human activities.

Stephanie Joyce