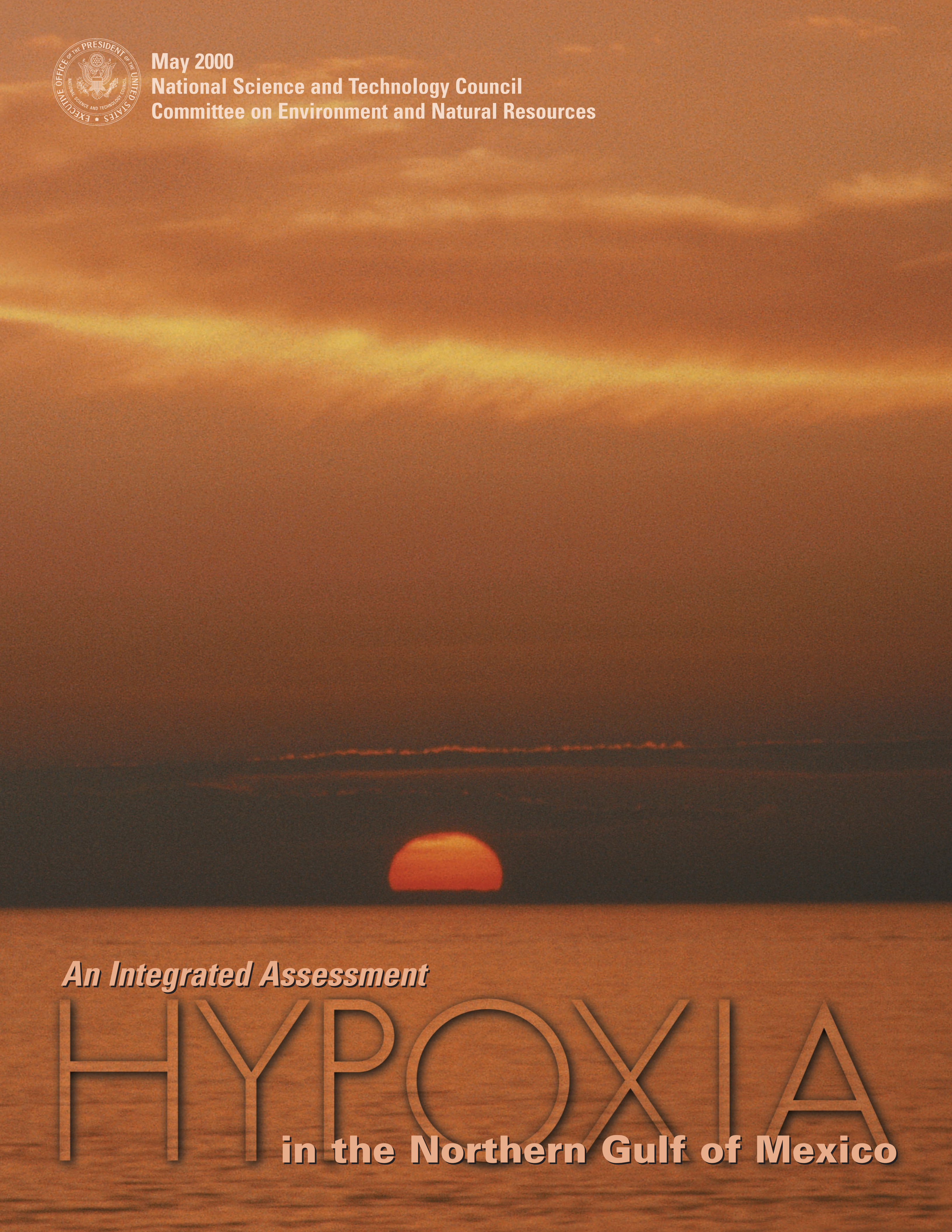

Executive Office of the President of the United States

May 2000
National Science and Technology Council
Committee on Environment and Natural Resources

An Integrated Assessment
HYPOXIA in the Northern Gulf of Mexico

The National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 13, 1993. This cabinet-level council is the principal means for the President to coordinate science, space, and technology policies across the federal government. The NSTC acts as a “virtual” agency for science and technology to coordinate the diverse parts of the federal research and development enterprise. Membership consists of the Vice President, the Assistant to the President for Science and Technology, cabinet secretaries, agency heads with significant science and technology responsibilities, and other White House officials.

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Integrated Assessment of Hypoxia in the Northern Gulf of Mexico

MAY 2000

National Science and Technology Council
Committee on Environment and Natural Resources

Committee on Environment and Natural Resources

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Acknowledgments

Hundreds of scientists, from a wide array of different fields, contributed over the years to the extensive knowledge base on which this assessment depends. An intensive collaborative effort over the past two years has assembled and reviewed available information. Special thanks are due to all who participated, particularly the many peer reviewers and the Editorial Board, whose efforts have sharpened thinking and clarified presentation.

Hypoxia Assessment Reports

As a foundation for the assessment, six interrelated reports that examine various aspects of the hypoxia issue were developed by six teams with experts from within and outside of government. The research teams were established not to conduct new research, but rather to analyze existing data and to apply existing models of the watershed-Gulf system. *This integrated assessment draws heavily from the results in these six reports.*

Each of the reports underwent extensive peer review by independent experts guided by an editorial board. Editorial Board members were Dr. Donald Boesch from the University of Maryland, Dr. Jerry Hatfield from the U.S. Department of Agriculture, Dr. George Hallberg from the Cadmus Group, Dr. Fred Bryan from Louisiana State University, Dr. Sandra Batie from Michigan State University, and Dr. Rodney Foil from Mississippi State University.

Topic 1. Characterization of Hypoxia. Describes the seasonal, interannual, and long-term variation of hypoxia in the northern Gulf of Mexico, and its relationship to nutrient loading. It also documents the relative roles of natural and human-induced factors in determining the size and duration of the hypoxic zone.

Nancy N. Rabalais, *Louisiana Universities Marine Consortium—Lead*
R. Eugene Turner, *Louisiana State University*
Dubravko Justić, *Louisiana State University*
Quay Dortch, *Louisiana Universities Marine Consortium*
William J. Wiseman, Jr., *Louisiana State University*

Topic 2. Ecological and Economic Consequences of Hypoxia. Presents an evaluation of the ecological and economic consequences of nutrient loading, including impacts on Gulf of Mexico fisheries and the regional and national economies.

Robert J. Diaz, *Virginia Institute of Marine Science—Ecological co-lead*
Andrew Solow, *Woods Hole Oceanographic Institution—Economics co-lead,*
with the assistance of many others

Topic 3. Flux and Sources of Nutrients in the Mississippi–Atchafalaya River Basin. Identifies the sources of nutrients within the Mississippi–Atchafalaya system and within the Gulf of Mexico, estimating both their location and the relative importance of specific human activities in contributing to these loads.

Donald A. Goolsby, *U.S. Geological Survey—Lead*
William A. Battaglin, *U.S. Geological Survey*
Gregory B. Lawrence, *U.S. Geological Survey*
Richard S. Artz, *National Oceanic and Atmospheric Administration*
Brent T. Aulenbach, *U.S. Geological Survey*
Richard P. Hooper, *U.S. Geological Survey*
Dennis R. Keeney, *Leopold Center for Sustainable Agriculture*
Gary J. Stensland, *Illinois State Water Survey*

Topic 4. Effects of Reducing Nutrient Loads to Surface Waters within the Mississippi River Basin and Gulf of Mexico. Estimates the effects of nutrient source reductions in the Mississippi–Atchafalaya Basin on water quality in these waters and on primary productivity and hypoxia in the Gulf.

Patrick L. Brezonik, *University of Minnesota—Upper watershed co-lead*
Victor J. Bierman, Jr., *Limno-Tech, Inc.—Gulf of Mexico co-lead*
Richard Alexander, *U.S. Geological Survey*
James Anderson, *University of Minnesota*
John Barko, *Waterways Experiment Station, U.S. Army Corps of Engineers*
Mark Dortch, *Waterways Experiment Station, U.S. Army Corps of Engineers*

Lorin Hatch, *University of Minnesota*
Gary L. Hitchcock, *University of Miami*
Dennis Keeney, *Iowa State University*
David Mulla, *University of Minnesota*
Val Smith, *University of Kansas*
Clive Walker, *Blackland Research Center*
Terry Whitledge, *University of Alaska*
William J. Wiseman, Jr., *Louisiana State University*

Topic 5. Reducing Nutrient Loads, Especially Nitrate–Nitrogen, to Surface Water, Ground Water, and the Gulf of Mexico. Identifies and evaluates methods to reduce nutrient loads to surface water, ground water, and the Gulf of Mexico.

William J. Mitsch, *The Ohio State University—Lead*
John W. Day, Jr., *Louisiana State University*
J. Wendall Gilliam, *North Carolina State University*
Peter M. Groffman, *Institute of Ecosystem Studies*
Donald L. Hey, *The Wetlands Initiative*
Gyles W. Randall, *University of Minnesota*
Naiming Wang, *The Ohio State University*

Topic 6. Evaluation of Economic Costs and Benefits of Methods for Reducing Nutrient Loads to the Gulf of Mexico. Evaluates the social and economic costs and benefits of the methods identified in Topic 5 for reducing nutrient loads, and assesses various incentive programs and any anticipated fiscal benefits generated for those attempting to reduce sources.

Otto C. Doering, *Purdue University—Lead*
Francisco Diaz-Hermelo, *Purdue University*
Crystal Howard, *Purdue University*
Ralph Heimlich, *Economic Research Service, U.S. Department of Agriculture*
Fred Hitzhusen, *The Ohio State University*
Richard Kazmierczak, *Louisiana State University*
John Lee, *Purdue University*
Larry Libby, *The Ohio State University*
Walter Milon, *University of Florida*
Tony Prato, *University of Missouri*
Marc Ribaudo, *Economic Research Service, U.S. Department of Agriculture*

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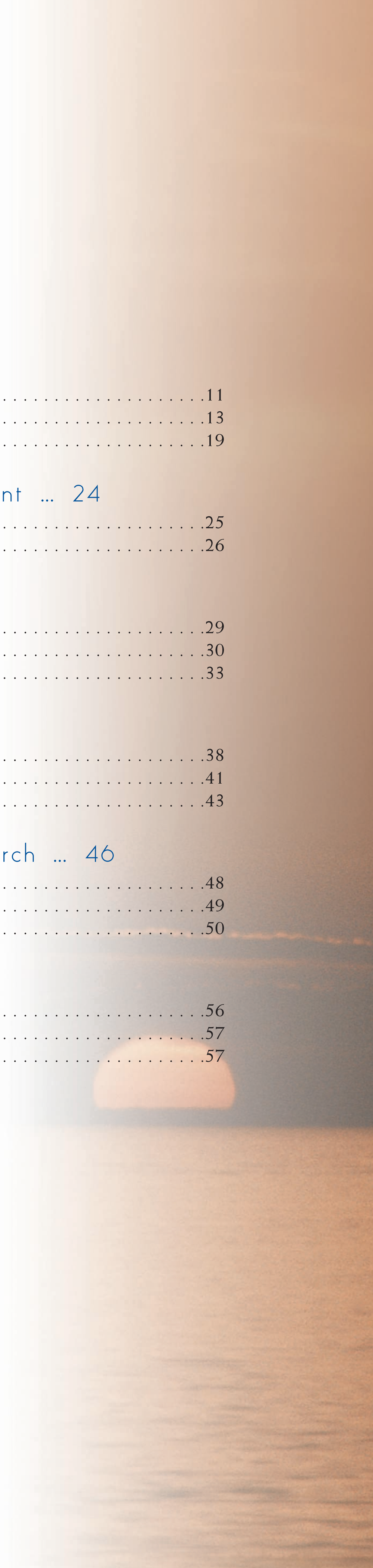


Executive Summary

Hypoxia occurs when dissolved oxygen concentrations are below those necessary to sustain most animal life. Since 1993, mid-summer bottom-water hypoxia in the northern Gulf of Mexico has been larger than 4,000 square miles. In 1999, it was 8,000 square miles, which is about the size of the state of New Jersey.

The Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 calls for an integrated assessment of causes and consequences of hypoxia in the Gulf of Mexico. The Act also calls for a plan of action to reduce, mitigate, and control hypoxia. While this integrated assessment is intended to provide scientific information for that Action Plan, it does not include recommendations for action, nor is it the only source of information that will be used to develop that plan.

Key Findings

Hypoxia in the northern Gulf of Mexico is caused primarily by excess nitrogen delivered from the Mississippi–Atchafalaya River Basin in combination with stratification of Gulf waters (Figure E.S. 1). Hypoxia results when oxygen consumption, primarily through decomposing organic material, exceeds oxygen production through photosynthesis and replenishment from the atmosphere. Organic matter can be supplied from external sources, such as river inflow, or can be produced within the system through algal growth stimulated by nutrients.

Sediment cores from the hypoxic zone show that algal production and deposition, as well as oxygen stress, were much lower earlier in the 1900s and that significant increases occurred in the latter half of the twentieth century. During this period, there have been three major changes in the drainage basin affecting the river nutrient flux. First, landscape alterations, such as deforestation and artificial agricultural drainage, removed most of the river basin's nutrient buffering capacity. Landscape alterations were greatest between 1875 and 1925, with a second peak of drainage development activity during 1945–60. Second, river channelization for flood control and navigation was completed prior to the 1950s, except structures that have maintained Atchafalaya flows at 30 percent of the combined flow of the Mississippi and Red Rivers since the mid-1970s. Third, major increases in fertilizer nitrogen input into the Basin occurred between the 1950s and 1980s, along with a large increase in nitrogen removal in harvested crops.

Since 1980, the Mississippi and Atchafalaya Rivers have discharged, on average, about 1.6 million metric tons of total nitrogen to the Gulf each year. Total nitrogen load has increased since the 1950s, due primarily to an increase in nitrate nitrogen. Nitrate flux to the Gulf of Mexico has almost tripled between the periods 1955–70 and 1980–96. Other forms of nitrogen, as well as organic carbon and phosphorus, have probably decreased over the twentieth century. No trend in dissolved inorganic nitrogen or total nitrogen flux has been observed since 1980, but these fluxes have become highly variable, depending on river discharge.

About 90 percent of the nitrate load to the Gulf comes from nonpoint sources. About 56 percent of the load enters the Mississippi River above the Ohio River, and the Ohio basin adds 34 percent. Principal sources are basins draining agricultural lands in Iowa, Illinois, Indiana, southern Minnesota, and Ohio.

Gulf ecosystems and fisheries are affected by hypoxia. Mobile organisms leave the hypoxic zone for healthier waters, and those that cannot leave die at varying rates, depending on how low the oxygen level gets and for how long. Fish, shrimp, zooplankton, and other important fish prey are significantly less abundant in hypoxic bottom waters.

Comparison of the distribution of fishing effort shows that the industry has shifted shrimping efforts away from hypoxic zones. Brown shrimp catch, the most economically important commercial fishery in the Gulf, declined from a record high in 1990 to below average during the years 1992–97, coinciding with years of greatly increased hypoxia. However, economic analysis of fisheries catch data did not reveal statistically significant effects that could be attributable to hypoxia.

FIG. E.S. 1 Mississippi–Atchafalaya River Basin and Gulf Hypoxic Zone

Source: Donald Goolsby and William Battaglin, U.S. Geological Survey.

The Mississippi–Atchafalaya River Basin is the largest river basin in North America, draining an area of 3.2 million square kilometers, or about 41 percent of the conterminous United States. River flux from the Basin to the Gulf of Mexico affects coastal areas where hypoxic conditions have been observed. This figure shows the extent of the hypoxic zone from a 1999 survey.

Water quality in the drainage basin has been degraded by excess nutrients. Most states in the Mississippi–Atchafalaya River Basin have significant river miles impaired by high nutrient concentrations, meaning that they are not fully supporting one or more resource uses, including aquatic life, fish consumption, and swimming. In some areas ground-water supplies are threatened by excess nitrate.

Potential Futures for Different Load Scenarios

If nutrient loads do not increase, the current size and severity of Gulf hypoxia and Basin water quality impairments would most likely remain the same. Hypoxia would vary annually, depending on the timing and extent of spring and summer stratification, weather patterns, temperature, and precipitation in the Gulf and drainage basin. This variability could alter the extent and severity of hypoxia, including creating new extreme increases or decreases.

Efforts to reduce loads may be offset by increases in population and food production and by climate change. If these other factors increase nutrient loads, hypoxia may expand. Because spawning grounds, migratory pathways, feeding habitats, and fishing grounds of important species are affected by the extent and duration of hypoxia, expanded hypoxia could lead to declines in productivity at higher levels of the food web and additional loss of essential habitat. At some point, fisheries and other species would be expected to decline, perhaps precipitously.

A 40 percent reduction in total nitrogen flux to the Gulf is necessary to return to loads comparable to those during 1955–70. Model simulations indicate that nutrient load reductions of about 20–30 percent would result in a 5–15 percent decrease in surface chlorophyll concentrations and a 15–50 percent increase in bottom-water dissolved oxygen concentrations. Such increases in oxygen concentrations are significant because they represent an overall average for the hypoxic zone, and any increase above the 2 mg/l threshold will have significant positive effects on marine life. Reduced nutrient loads to surface waters in the Basin would also be expected to decrease nutrient concentrations in its rivers and streams. These changes should induce positive changes in trophic conditions and result in Basin-wide improvements in surface-water quality.

Considerations for Taking Action

In many areas, significant efforts to reduce nutrient flux to surface waters are already underway. This assessment is based primarily on conditions observed through the mid-1990s; thus, current activities may be having effects that have not yet been documented. Based on these basin-scale analyses, the primary approaches to reduce hypoxia in the Gulf of Mexico appear to be to: (1) reduce nitrogen loads to streams and rivers in the Basin and (2) restore and enhance denitrification and nitrogen retention within the Basin. Another potential approach might be to divert water from the Mississippi and Atchafalaya Rivers directly to areas of the Gulf not currently experiencing hypoxia. However, such an approach would have multiple consequences, none of which have been analyzed.

While this assessment suggests that changes in agricultural practices could provide many elements of a solution at least cost to society overall, analyses contributing to this assessment identified several possible approaches to sharing the burden of nutrient load reductions among all sectors in the Mississippi drainage. There are no single solutions to managing hypoxia in the Gulf. An optimal approach would take advantage of the full range of possible actions to reduce nutrient loads and increase nutrient retention and denitrification within a framework that encourages adaptive management. Such an approach could be initiated within the existing array of state and federal laws and programs.

In this assessment, a national model of the agriculture sector was used to examine many of the economic effects and the changes in nitrogen loading under various scenarios. While specific actions at local levels will most likely require analyses at higher spatial resolution, the following findings should be considered when developing a plan of action for improving Basin and Gulf water quality and habitat.

Management practices that retain more nitrogen on fields—including applying nitrogen fertilizer at not more than recommended rates, implementing alternative cropping systems, and improving manure management—as well as reducing nitrogen flux from point sources will reduce nitrogen loads to rivers and streams. Reducing nitrogen loss at the edge of the field by 20 percent through a combination of economically optimal improvements in farming practices would be expected to cost producers and consumers (net cost) about $0.40 per pound of nitrogen reduction. For comparison, reduction in fertilizer use alone (without other changes in farming practices) was modeled at several levels. A 45 percent reduction in fertilizer use would be required to generate a comparable (20 percent) reduction of edge-of-field loss at a cost of about $1.30 per pound, while a 20 percent reduction in fertilizer use would be required to achieve a 10 percent edge-of-field loss at about $0.31 per pound. (Note that these estimates of the impacts of changes in agricultural practices are for reductions at the "edge of the field," the location where sediment and nutrients leave the farm. Estimated edge-of-field source reductions do not translate to equivalent reductions in nitrogen loading to the Gulf, as only a portion of nitrogen sources in the Basin reaches the Gulf.)

Other measures to reduce nitrogen loads to rivers and streams, such as reducing urban point and nonpoint sources and atmospheric deposition, could provide important contributions in some instances. Average costs of reducing point sources and atmospheric deposition are about $5–50 per pound. In addition, nitrogen trading among all sectors could offer opportunities to obtain least-cost reductions.

Increasing the acreage of wetlands and vegetated riparian buffers within the Basin would enhance denitrification (a process that removes nitrogen from the system) increase nitrogen retention, and decrease the amount of nitrogen entering streams and rivers. Model analyses demonstrate that the most effective use of restored and created wetlands would be in watersheds that discharge high amounts of nitrogen. At typical denitrification rates for flow-through wetlands, 5 million acres of wetlands would reduce nitrogen load to the Gulf by 20 percent and would cost $4.05 per pound of nitrogen denitrified. An estimated 19 million acres of additional riparian buffers would be needed to reduce nitrogen load to the Gulf by the same amount.

Reintroducing river water to the backwaters, coastal wetlands, and shallow inshore bodies of water on the Louisiana delta could augment efforts to reduce nutrient inputs from the upstream sources and could also help to reduce the rate of coastal land loss. However, diversions have potential deleterious effects, such as eutrophication of embayment estuaries receiving the flows, that must also be considered.

All of these nutrient-reduction approaches are expected to produce other important economic and environmental benefits within the drainage basin. These include those associated with restored wetlands, reduced soil erosion, reduced nutrient contamination of drinking water, reduced vulnerability to floods, improved water quality for recreational uses, and improved fish and wildlife habitat in streams, lakes, rivers, and estuaries. Other potential benefits include more efficient use of fertilizers and the energy associated with them, and lower overall fertilizer costs. However, reliable estimates of the economic value of these benefits are only available for a few categories, such as wetlands and erosion. When only these benefits are included in the analysis, the net unit costs of wetlands creation and improved farm practices are comparable. Accounting for some benefits, reducing edge-of-field nitrogen loss by 20 percent through improved farm practices has an approximate net cost of $0.36 per pound. Reducing nitrogen flux from the river to the Gulf by 20 percent through wetland restoration and creation has an approximate net cost of $0.45 per pound when those benefits are considered.

Adaptive Management: Coupling Monitoring, Research, and Action

The complex nature of nutrient cycling and transport within the Basin and the Gulf of Mexico requires an adaptive management framework. Also, the potentially lengthy period of time required to observe changes resulting from management action calls for an adaptive management scheme. Such an approach provides a comprehensive, carefully targeted program of monitoring, modeling, and research to facilitate continual improvement in scientific knowledge and gradual adaptation of management approaches. This adaptive management scheme will require a long-term commitment to monitoring, research, and assessment and continual feedback between interpretations of new information and management actions. A comprehensive monitoring program is needed to measure environmental pressures and responses, and programmatic progress in the Gulf and in the Basin.

The work synthesized in this assessment significantly advances our understanding; however, specific uncertainties remain. Immediate priorities for reducing these uncertainties include research on the ecological effects of hypoxia; watershed nutrient dynamics, particularly between the edge of the field and stream; and the effects of different agricultural practices on nutrient losses from land. Longer-term priorities include research on nutrient cycling and carbon dynamics, long-term changes in hydrology and climate, as well as economic and social impacts.

The Problem

of Hypoxia in the Northern Gulf of Mexico

Nearly all marine animals depend on oxygen dissolved in the water. Where oxygen depletion is severe, the food web that supports bottom feeders, such as shrimp and drum, is disrupted, as well as the natural processing of organic matter, nutrients, and pollutants. Growth of marine organisms is inhibited when dissolved oxygen is less than about 5 mg/l. Mobile organisms leave as dissolved oxygen levels decrease below 2 mg/l, and trawlers in these areas produce little or no catch. Burrowing organisms first emerge from the sediment, and then die, if oxygen concentrations remain near 0.5 mg/l for prolonged periods. In areas where the oxygen concentrations are below 0.2 mg/l, the sediment is typically black, and sulfur-oxidizing bacteria form mats on the seafloor. Toxic hydrogen sulfide may be found where bottom waters are completely devoid of oxygen (anoxic).

Hypoxia is the condition in which dissolved oxygen is below the level necessary to sustain most animal life—generally defined by dissolved oxygen levels below 2 mg/l (or ppm). The largest hypoxic zone in U.S. coastal waters—and in the entire western Atlantic Ocean—is found in the northern Gulf of Mexico on the Louisiana/Texas continental shelf (Figure 1.1). The area affected, which is about the size of the state of New Jersey, has increased since regular measurements began in 1985 (Figure 1.2).

The fishery resources of the Gulf are among the most valuable in the United States, generating $2.8 billion annually. Although economic analyses have not shown a statistically significant correlation with the extent of hypoxia, catch per unit of effort for brown shrimp, one of the most commercially valuable species in the Gulf, has trended down since the late 1970s. If experiences in other coastal and marine systems are applicable to the Gulf of Mexico, then the potential impact of worsening hypoxic conditions could be the decline (perhaps precipitous) of ecologically and commercially important species.

In October 1998, Congress passed the Harmful Algal Bloom and Hypoxia Research and Control Act, which the President signed into law as P.L.105-383 on November 13, 1998. This law calls for an "integrated assessment of hypoxia in the northern Gulf of Mexico that examines: the distribution, dynamics and causes; ecological and economic consequences; sources and loads of nutrients transported by the Mississippi River to the Gulf of Mexico; effects of reducing nutrient loads; methods for reducing nutrient loads; and the social and economic benefits of such methods." P.L.105-383 also calls for the development of a plan of action to reduce, mitigate, and control hypoxia in the northern Gulf of Mexico. The Action Plan will be developed by the Mississippi River/Gulf of Mexico (MR/GM) Watershed Nutrient Task Force. This integrated assessment is intended to provide scientific information to both specialists and nonspecialists as a basis for the Action Plan. This assessment does not make specific recommendations for action, nor is it the only source of information that the MR/GM Task Force will consider in developing the Action Plan.

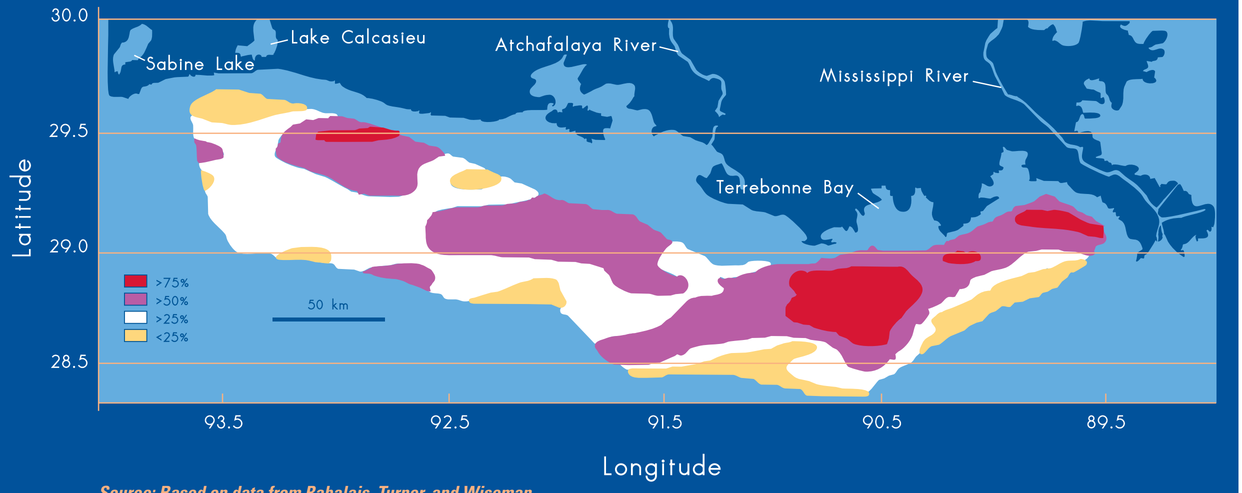
> The potential impact of worsening hypoxic conditions could be the decline (perhaps precipitous) of ecologically and commercially important species.

The National Science and Technology Council's Committee on Environment and Natural Resources had already taken steps in 1997 to assess the state of scientific knowledge and understanding of Gulf of Mexico hypoxia, and by March 1998 it had developed and approved an assessment plan in conjunction with the MR/GM Task Force. The plan called for six teams of experts from inside and outside of government to develop six reports that examine various interrelated aspects of hypoxia. The teams were established to review and analyze existing data and apply existing models of the watershed–Gulf system. The six peer-reviewed reports are based on a massive amount of direct and indirect evidence collected and reported over many years of scientific inquiry, including in-depth studies of oceanographic, hydrologic, agricultural, economic, and other questions related to the issue of hypoxia in the Gulf.[1]

This integrated assessment draws heavily from the six reports, freely using both their findings and their words, and explicitly cites them only when it refers to specific information a reader may want to examine in greater detail. The assessment summarizes the state of knowledge of the extent, characteristics, causes, and effects

The frequency of occurrence of hypoxia has been mapped from mid-summer "snapshots" obtained by sampling a 60- to 80-station grid in the Gulf annually from 1985 through 1999.

FIG. 1.1 Frequency of Occurrence of Hypoxia in the Gulf of Mexico: 1985–99



Source: Based on data from Rabalais, Turner, and Wiseman.

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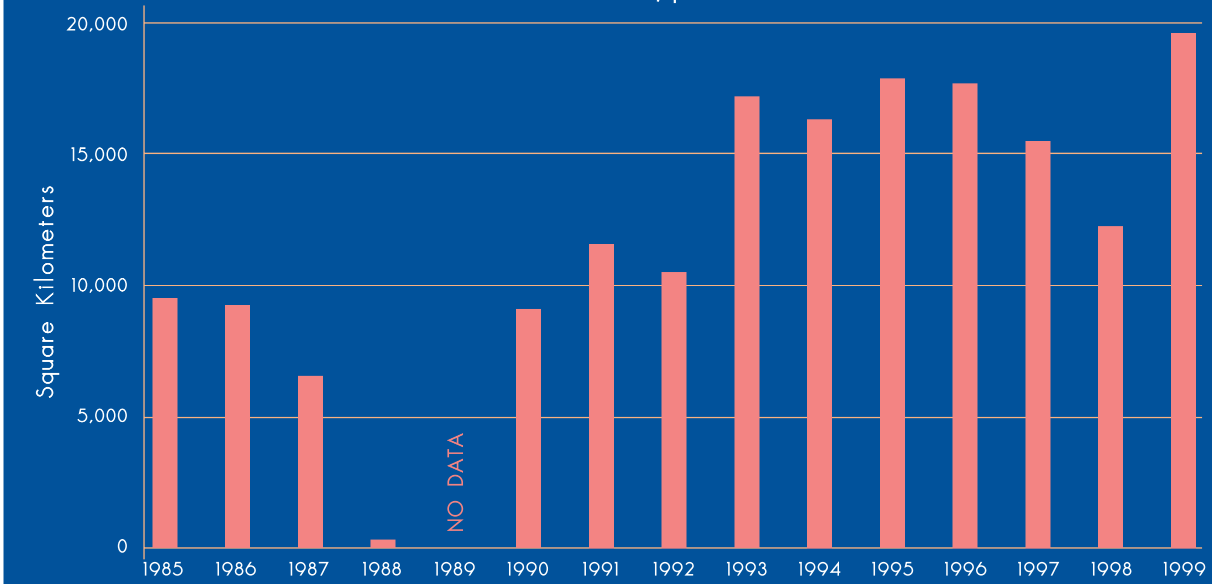
[1] *The six topic reports underwent a rigorous peer review with oversight by an independent editorial board. In addition, the six topic reports were available for a 90-day public comment period. The reports and the comments received on them are available at <http//www.nos.noaa.gov/products/pubs_hypox.html>. This assessment has been written with consideration of all that information. The assessment was available, in draft form, for a 60-day public comment period. Those comments are also posted on this web site and were carefully considered in producing the assessment in this final version.*

FIG. 1.2 Areal Extent of Mid-summer Hypoxia: 1985–99



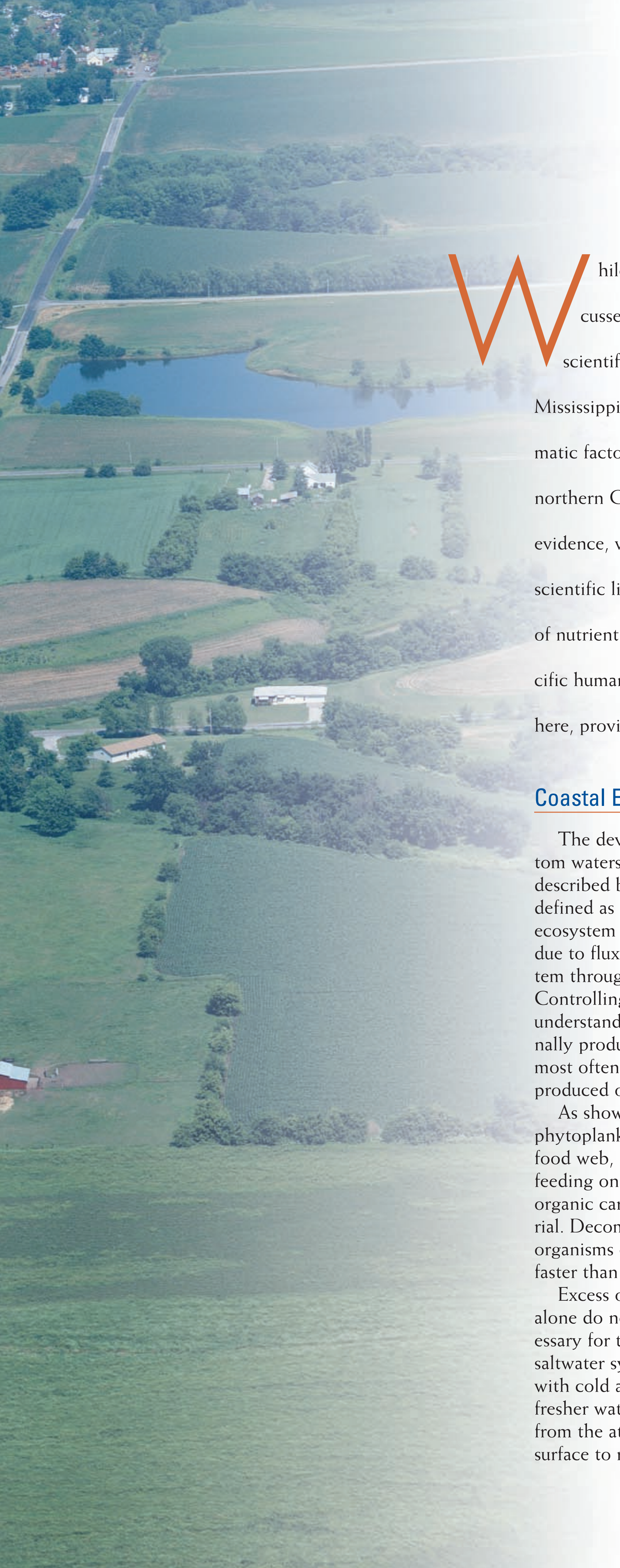
Source: Nancy Rabalais, Louisiana Universities Marine Consortium.

Annual mid-summer cruises have been conducted systematically over the past 15 years (with the exception of 1989). Hypoxia in bottom waters covered an average of 8,000–9,000 km^2 in 1985–92 but increased to 16,000–20,000 km^2 in 1993–99.

of hypoxia in the northern Gulf of Mexico. It outlines a range of approaches for reducing those effects and examines the costs and benefits associated with those approaches. It also describes additional research and monitoring needed to reduce uncertainties, to track progress following any efforts developed in the Action Plan, and to identify potential future adjustments to any initial actions that may be taken to reduce hypoxia and improve water quality.

The Causes

of Hypoxia in the Northern Gulf of Mexico



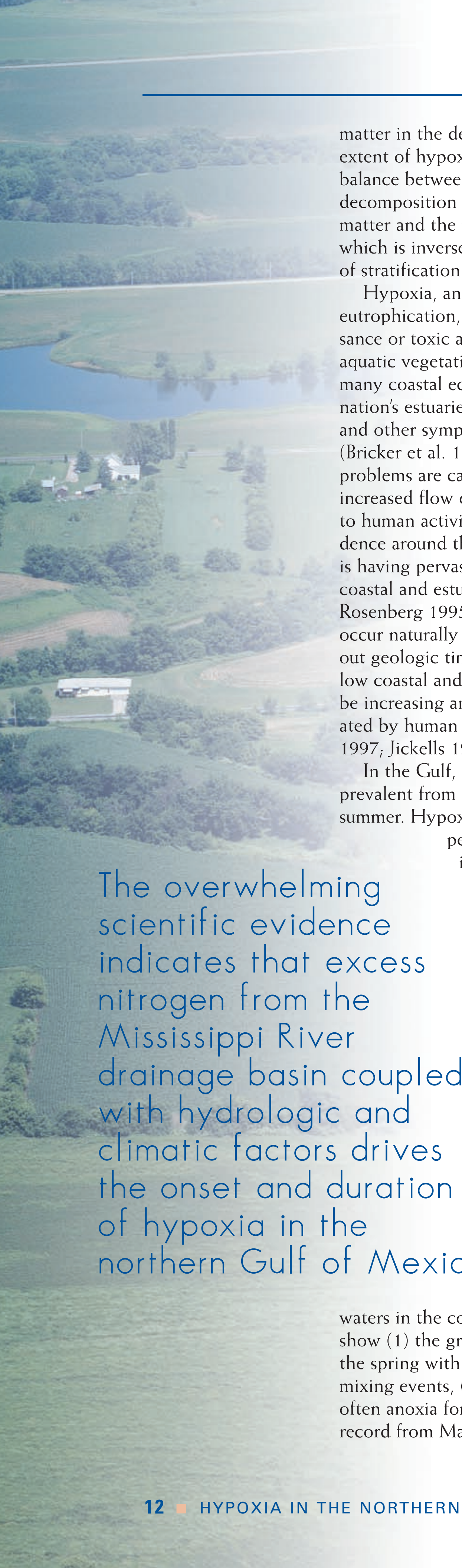
While information gaps still exist and several factors discussed below may contribute to hypoxia, the overwhelming scientific evidence indicates that excess nitrogen from the Mississippi River drainage basin coupled with hydrologic and climatic factors drives the onset and duration of hypoxia in the northern Gulf of Mexico. The following section summarizes this evidence, which is described in the detailed topic reports and the scientific literature upon which this assessment is based. Analysis of nutrient trends and sources, and the relative importance of specific human activities in contributing to these trends, are described here, providing the basis for the chapters that follow.

Coastal Eutrophication

The development of hypoxia in northern Gulf of Mexico bottom waters, as well as in most ocean and freshwater systems, is described best by the eutrophication process. Eutrophication is defined as an increase in the rate of supply of organic matter in an ecosystem (Nixon 1995). This increase in organic matter can be due to flux from external sources or to production within the system through biological processes stimulated by nutrient addition. Controlling or reversing the effects of eutrophication necessitates understanding the relative roles of externally supplied and internally produced organic carbon. Externally supplied organic carbon most often comes from wetlands or uplands via rivers. Internally produced organic carbon comes from the growth of algae.

As shown in Figure 2.1, nutrients stimulate production of phytoplankton algae. Algae that are not incorporated into the food web, fecal products, and other debris from zooplankton feeding on algae, together with externally supplied particulate organic carbon, sink into bottom waters as "excess" organic material. Decomposition of this organic material by bacteria and other organisms consumes oxygen, and when the consumption rate is faster than its replenishment, oxygen concentrations decrease.

Excess organic carbon and subsequent oxygen consumption alone do not necessarily lead to hypoxia: stratification is also necessary for the development of hypoxia in bottom waters. In most saltwater systems, the water stratifies (creating horizontal layers), with cold and/or saltier water at the bottom and warmer and/or fresher water at the surface. This layering separates bottom waters from the atmosphere and prevents re-supply of oxygen from the surface to replenish deficits created by the decomposing organic



matter in the deeper waters. Thus, the extent of hypoxia is determined by the balance between the rate of delivery and decomposition of algae and other organic matter and the rate of oxygen re-supply, which is inversely related to the strength of stratification.

Hypoxia, and other symptoms of eutrophication, such as growth of nuisance or toxic algae and loss of submerged aquatic vegetation, are major stresses in many coastal ecosystems. Over half of the nation's estuaries experience low oxygen and other symptoms of eutrophication (Bricker et al. 1999). Almost all of these problems are caused or exacerbated by the increased flow of nutrients from land due to human activities. There is growing evidence around the world that low oxygen is having pervasive effects on shallow coastal and estuarine areas (Diaz and Rosenberg 1995). While hypoxia can occur naturally and has existed throughout geologic time, its occurrence in shallow coastal and estuarine areas appears to be increasing and is most likely accelerated by human activities (Vitousek et al. 1997; Jickells 1998).

In the Gulf, hypoxic waters are most prevalent from late spring through late summer. Hypoxia is more widespread and persistent in some years than in others, depending on river flow, winds, and other environmental variables. Hypoxic waters are distributed from shallow depths near shore (4 to 5 meters) to as deep as 60 meters but more typically appear between 5 and 30 meters. Hypoxia occurs mostly in the lower water column but encompasses as much as the lower half to two-thirds of the entire column. Continuous time-series data for the bottom waters in the core of the hypoxia region show (1) the gradual decline in oxygen in the spring with interruptions due to wind-mixing events, (2) persistent hypoxia and often anoxia for extended parts of the record from May through September, (3) occasional summer upwelling of oxygenated water from the deeper shelf waters, and (4) the seasonal disruption of low oxygen in the fall by tropical storms or cold fronts.

The overwhelming scientific evidence indicates that excess nitrogen from the Mississippi River drainage basin coupled with hydrologic and climatic factors drives the onset and duration of hypoxia in the northern Gulf of Mexico.

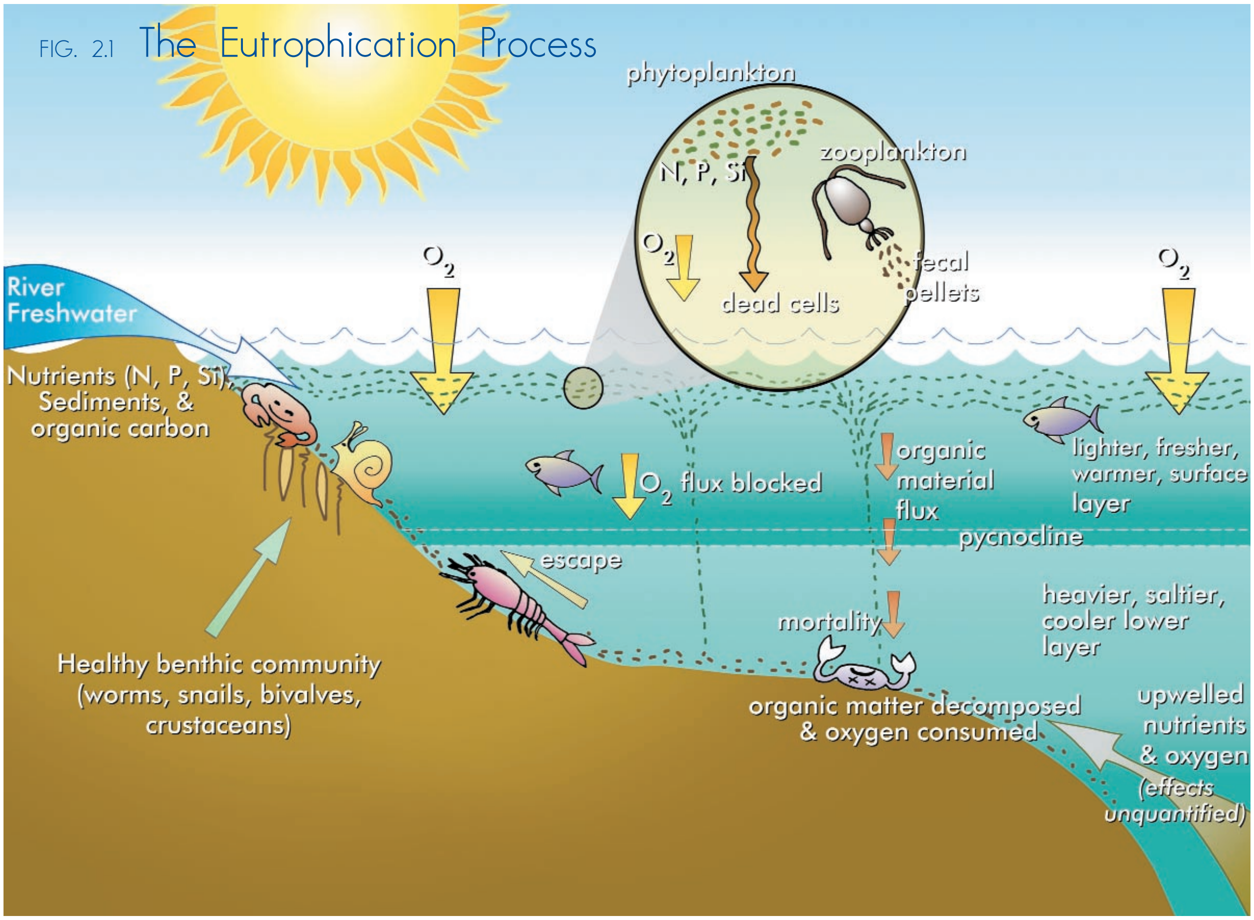
Role of Nutrients

Nitrogen is the most significant nutrient controlling algal growth in coastal waters, while phosphorus is the most significant nutrient in fresh water (NRC 1993). Silicon also plays an important role in that it regulates the production of diatoms, which are a type of algae important as food for fish and invertebrates. Diatoms, unlike other phytoplankton species, require silicon to build their cell walls and are the dominant biomass component of many marine and estuarine phytoplankton communities, particularly in the spring. If silicon supply is limited relative to the other nutrients, then nonsiliceous algae, such as dinoflagellates and cyanobacteria, may become proportionately more important in the phytoplankton community. Some of these forms are harmful or toxic. The ratios among dissolved silica, nitrogen, and phosphorus in the lower Mississippi River now closely approximate the typical ratio of these nutrients in diatoms. Thus, while nitrogen is the nutrient that controls the quantity of coastal algal production, significant changes in the relative composition of nutrient supplies may also lead to important alterations in the type of algae present.

Role of Stratification

If Louisiana shelf waters did not stratify, hypoxia would be unlikely. However, the river and Gulf oceanography create a strongly stratified system each year, characterized by relatively warm and fresher water that forms a high-production lens over the deeper salty, colder waters. The greater the density difference (related to temperature and salinity) between layers, the more stable the stratification. Very strongly stratified systems require a lot of wind energy—sometimes a tropical storm—in order to mix. If storms do not mix the waters, they will remain in layers, isolating bottom waters from aeration until fall brings cooler surface temperatures and the density of the surface water approaches that of the bottom water.

FIG. 2.1 The Eutrophication Process



Eutrophication occurs when organic matter increases in an ecosystem. Eutrophication can lead to hypoxia when decaying organic matter on the seafloor depletes oxygen, and the replenishment of the oxygen is blocked by stratification. The flux of organic matter to the bottom is fueled by nutrients carried by riverflow or, possibly, from upwelling that stimulates growth of phytoplankton algae. This flux consists of dead algal cells together with fecal pellets from grazing zooplankton. Organic carbon from the Mississippi River can also contribute to the flux of organic matter.

Role of Other Potentially Contributing Factors

In addition to high levels of nutrients, other factors potentially contribute to hypoxia in the Gulf. The most significant of these other factors are described in the box on the next two pages. Only increased nitrogen loads from the Mississippi–Atchafalaya River system can account for the magnitude of the hypoxic zone and its increase over time. While other factors may contribute to the growth, dynamics, and decline of the hypoxic zone, none of them alone can explain its overall size and persistence.

Internally produced organic carbon, stimulated by nutrients (from the land, air, or sea), externally supplied organic carbon, horizontal stratification, ocean circulation, and river hydrology are not competing hypotheses. Rather, they are interacting factors within the eutrophication process as it takes place in the Gulf of Mexico. These factors have been discussed in the six technical background papers, in the comments on those papers, at a science meeting on these issues held December 3, 1999,[2] and in recent reports on this subject sponsored by the Fertilizer Institute (Carey et al. 1999) and the Council for Agricultural Science and Technology (Downing et al. 1999), as well as the wide range of previous work summarized in such volumes as the *1995 Proceedings of the First Gulf of Mexico Hypoxia Management Conference* (EPA 1997) and the December 1994 and June 1996 special issues of *Estuaries*.

Nutrient Over-Enrichment

The evidence for nutrient over-enriched production in the northern Gulf of Mexico and its linkage with oxygen depletion in the lower water column is consistent with the eutrophication process, with data and experiences worldwide, and with Gulf- and basin-specific information on a variety of scales.

Scientific investigations over the last several decades indicate

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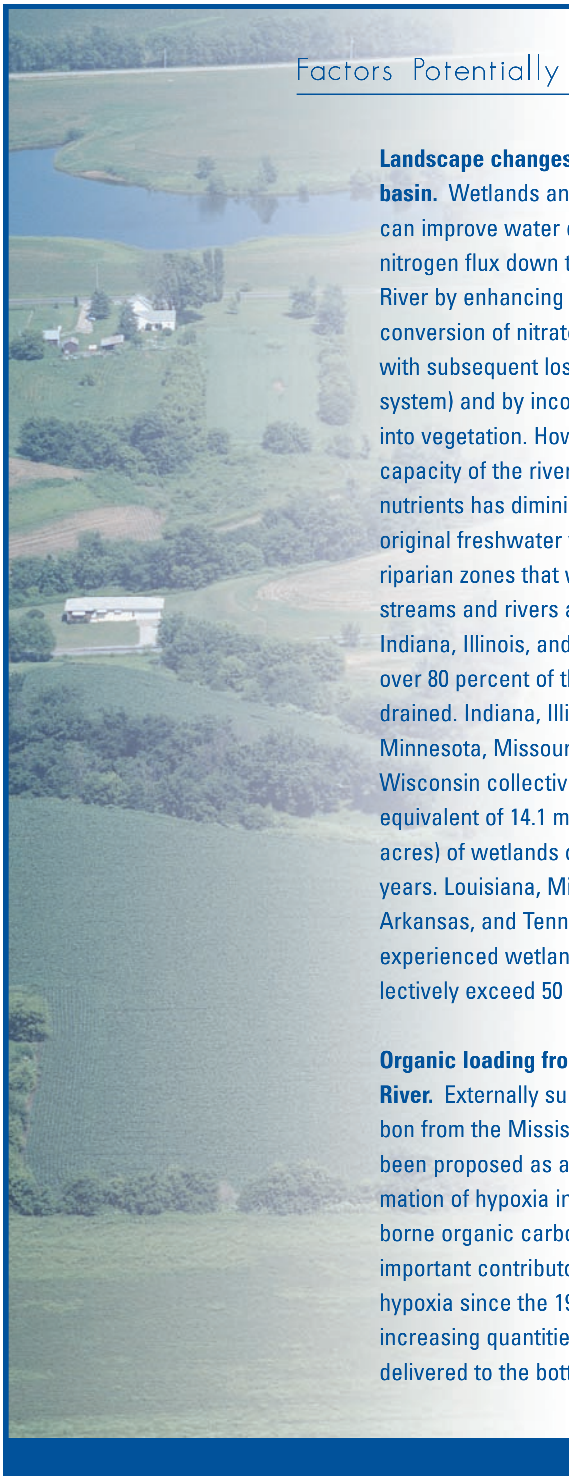
[2] *Notes from the December 3, 1999, science meeting can be found at <http://www.nos.noaa.gov/products/pubs_hypox.html>*

overwhelmingly that oxygen stress in the northern Gulf of Mexico is caused primarily by excess nutrients delivered to Gulf waters from the Mississippi–Atchafalaya River drainage basin, in combination with the stratification of Gulf waters.

This section outlines the scientific evidence supporting river nutrient loads as the primary factor fueling hypoxia in the Gulf of Mexico through over-enrichment. It is supported by analysis of the sources and loads, as described in the next section.

Trends in Indicators of Production, Low-Oxygen Stress, and River Nutrient Flux

Analysis of river discharge data and sediment cores from the Louisiana shelf in the Mississippi River delta bight indicate that



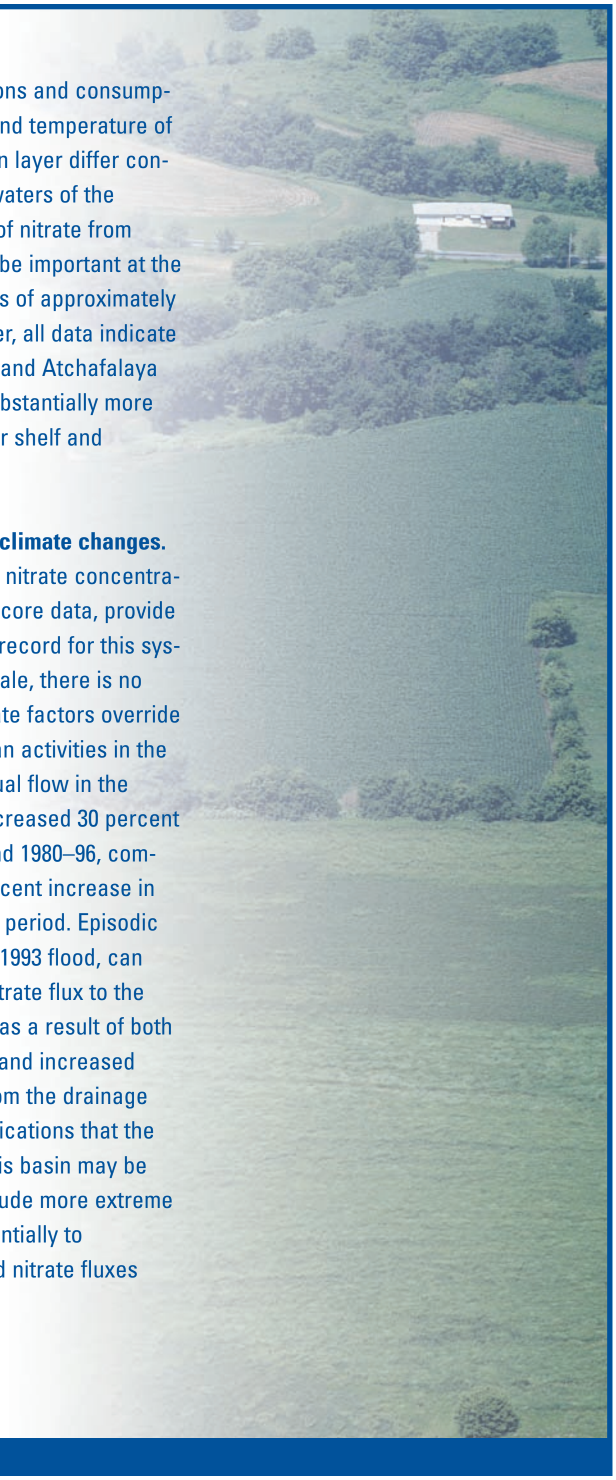
Factors Potentially Contributing to Hypoxia in the Gulf

Landscape changes in the drainage basin. Wetlands and riparian zones can improve water quality and reduce nitrogen flux down the Mississippi River by enhancing denitrification (the conversion of nitrate to nitrogen gas, with subsequent loss from the aquatic system) and by incorporating nitrogen into vegetation. However, the natural capacity of the river basin to remove nutrients has diminished. Many of the original freshwater wetlands and riparian zones that were connected to streams and rivers are gone. Ohio, Indiana, Illinois, and Iowa have had over 80 percent of their wetlands drained. Indiana, Illinois, Iowa, Minnesota, Missouri, Ohio, and Wisconsin collectively have lost the equivalent of 14.1 million ha (35 million acres) of wetlands over the past 200 years. Louisiana, Mississippi, Arkansas, and Tennessee have also experienced wetland losses that collectively exceed 50 percent.

Organic loading from the Mississippi River. Externally supplied organic carbon from the Mississippi River has been proposed as a cause of the formation of hypoxia in the Gulf. For river-borne organic carbon to be an important contributor to the rise in hypoxia since the 1950s, significantly increasing quantities would have to be delivered to the bottom waters of the hypoxic zone and would have to be decomposed by bacteria. Only the particulate organic carbon (POC) fraction of the total organic carbon load could contribute directly to hypoxia because only that fraction would sink to the bottom waters. The dissolved fraction would remain in the river-freshened surface waters and would have to be biologically assimilated and deposited as newly formed POC, with large attendant respiratory losses, to reach hypoxic zones extending 100–200 km from the river discharges. Suspended sediment in the river has declined by about half since the 1950s, so the POC load that can settle on the Louisiana shelf has also most likely decreased since then. Also, nutrient cycling affords nitrogen the ability to stimulate production of organic carbon at rates that far surpass that supplied by the river. Whereas decomposition of river-supplied organic carbon consumes oxygen only once, river-supplied nitrogen can be recycled and thus provides a continuous source of comparatively easily decomposed organic carbon (Ryther and Dunstan 1969). Scientists reviewed evidence about the role of organic carbon at a December 1999 meeting and agreed that it is a relatively small factor driving hypoxia—nitrogen-driven carbon production is approximately an order of magnitude greater.

eutrophication and hypoxia in the northern Gulf increased coincidentally with increases in nitrogen loads from the Mississippi River. The data exhibit both long-term trends and short-term variations. One particularly important factor is that peak river flows have increased over the past 150 years due primarily to land-use changes, flood-control and navigation projects in the river, and climate (precipitation) changes.

Long-term Records—Gulf Ecosystem Changes. Since there are no comprehensive, direct measurements of oxygen in the northern Gulf of Mexico prior to 1985, evidence for long-term changes in hypoxia is based on indirect analysis from sediment records. While it is possible to explore temporal changes in water-column production,

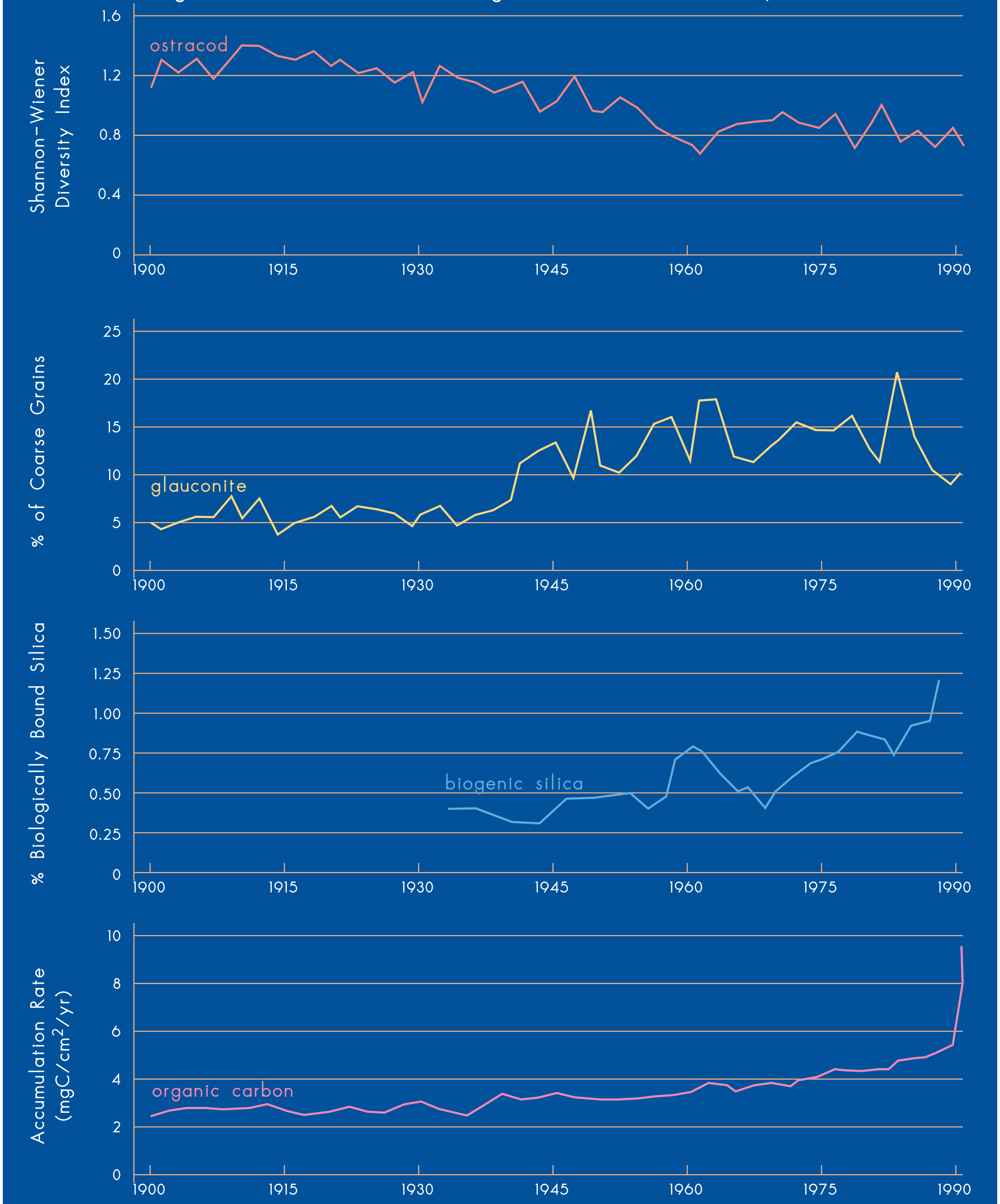


Channelization of the delta and loss of coastal wetlands. Although in some years over-bank flow has been significant, flooding through coastal wetlands has been reduced since the 1927 flood, but geochemical and biological indicators show that hypoxia has intensified only since the 1950s. Coastal wetland loss rates exceeded 100 km^2 (about 40 sq mi) per year between 1950 and 1980. Recent wetland protection and restoration programs helped reduce losses in the 1990s to 65–90 km^2 (about 25–35 sq mi) per year. Both the loss of wetland filtering capacity and the direct contribution of organic matter eroded from wetlands and carried to the Gulf may contribute to the problems of hypoxia; however, the total contribution is relatively small compared with the nitrogen-related factors. Further, carbon isotope analysis shows that the sources of carbon over the broad area affected by hypoxia is produced by marine phytoplankton and is distinct from carbon close to shore.

Intrusion of deeper offshore waters. Some have suggested that flow of low-oxygen water from water layers in the deeper Gulf on to the continental shelf was the source of shelf hypoxia. However, these features are always physically distinct, with the shelf hypoxic zone at depths of less than 60 meters, and the deep low-oxygen layer at depths of 400–700 meters. Further, oxygen concentrations and consumption rates, salinity, and temperature of the deep low-oxygen layer differ considerably from the waters of the hypoxic zone. Flow of nitrate from deeper waters may be important at the shelf edge (at depths of approximately 100 meters); however, all data indicate that the Mississippi and Atchafalaya Rivers contribute substantially more nutrients to the inner shelf and hypoxic region.

Short- or long-term climate changes. River discharge and nitrate concentrations, and sediment core data, provide almost 100 years of record for this system. On that time scale, there is no indication that climate factors override the impacts of human activities in the basin. Average annual flow in the Mississippi River increased 30 percent between 1955–70 and 1980–96, compared to the 300 percent increase in nitrate flux over this period. Episodic events, such as the 1993 flood, can nearly double the nitrate flux to the Gulf in a given year as a result of both higher-volume flow and increased loading of nitrate from the drainage basin. There are indications that the future climate for this basin may be wetter and may include more extreme events, leading potentially to increased water and nitrate fluxes (Kunkel et al. 1999).

FIG. 2.2 Long-term Records of Changes in the Gulf Ecosystem: 1900–90



Sources: Figures 7.6, 7.7, and 7.9 in the Topic 1 Report for the Integrated Assessment.

Profiles from cores taken in the Mississippi River bight in an area of persistent seasonal bottom-water hypoxic conditions revealed the following trends related to the growth of bottom-water hypoxia in the area: (1) a steady decrease in the number of species of ostracods, a family of minute shelled organisms; (2) an increase in the abundance of the mineral glauconite, which forms only under low-oxygen conditions; (3) an increase in the average concentration of biologically bound silica, indicating changes in algal community composition; and (4) an increase in the organic carbon accumulation rates, indicating growth in algal production.

oxygen-relevant geochemistry, and biology because such properties are preserved sequentially down a sediment core, it is important to recognize that bottom mixing and sediment reworking limits the resolution of temporal change to scales approaching decades, as opposed to years.

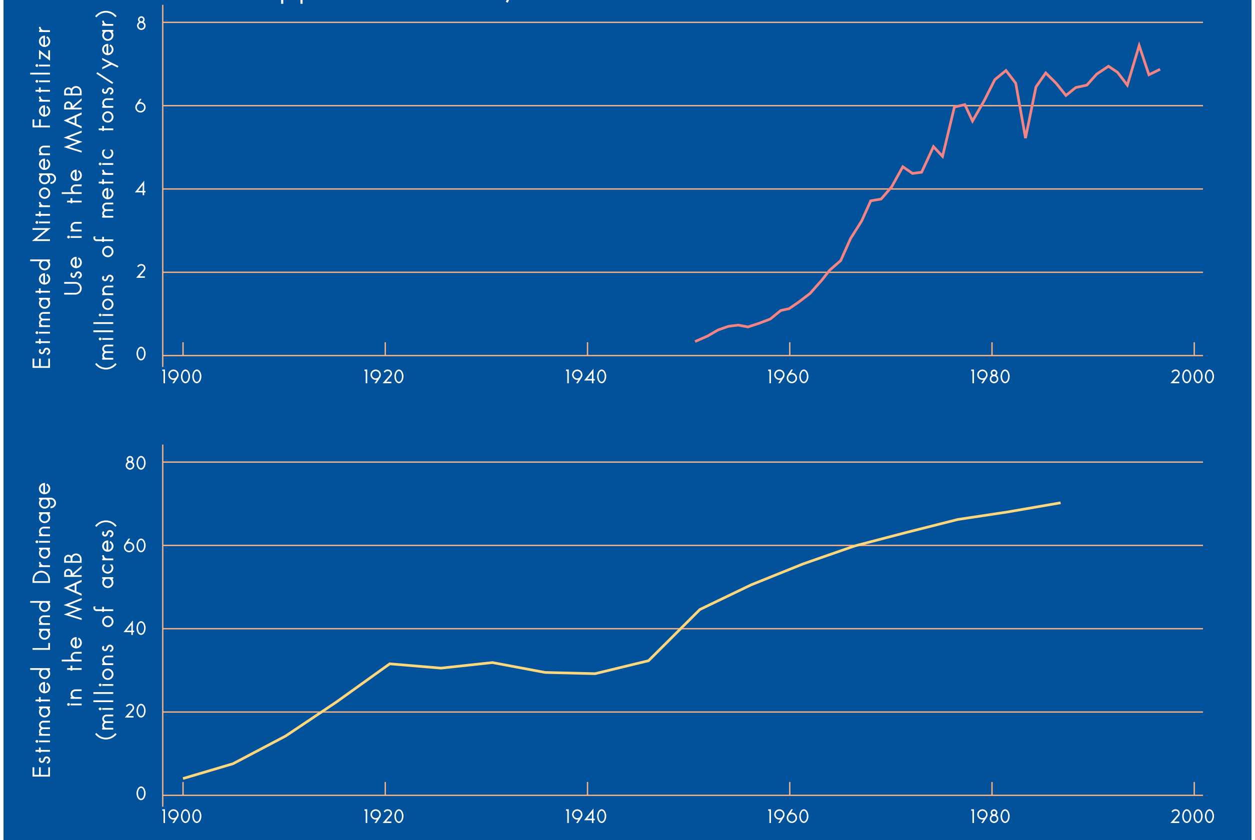
The data shown in Figure 2.2 are from cores collected within one area of the current hypoxic zone. Therefore they do not necessarily represent the timing of the transitions for the entire contemporary hypoxic zone. They do, however, clearly show that algal production and deposition, as well as oxygen stress, were much lower earlier in the twentieth century and that significant changes have occurred in the latter half of the century.

The sediment record clearly shows significant increase in algal production beginning around the 1950s. Accumulation of organic carbon and biogenic silica (a measure of diatom abundance) both increased significantly after that time period. Because there have been no significant increasing trends in either the organic carbon or the silica river loads, it is reasonable to infer that these increases in the sediment record since the 1950s are due to production of marine algae.

The sediment geochemistry record indicates that while there was likely some oxygen stress on the Louisiana shelf as early as the beginning of the twentieth century, there was a striking increase in that stress starting roughly during the 1940s and 1950s. Because the mineral glauconite forms only under reducing conditions, its presence in the sediment is an indication of low oxygen conditions. Sediment cores show the history of glauconite formation from sediments as they were deposited on the seafloor. As shown in the core profile in Figure 2.3, glauconite abundance was relatively low in the early 1900s, but increased dramatically in the 1940s and 1950s, indicating increased low oxygen stress.

Another indirect indicator of a significant change in the relative magnitude of hypoxia during this same transition period is the biodiversity of benthic foraminifera and ostracods preserved in the sediments. These single-celled

FIG. 2.3 Long-term Records of Changes in the Mississippi-Atchafalaya River Basin: 1900-99



Sources: Figure 5.7 of the Topic 3 Report for the Integrated Assessemnt; and Figure 1.2 of the Topic 5 Report.

The amount of nitrogen fertilizer used in the Basin increased dramatically between the 1950s and 1980s (enabling a large increase in crop production). The area of cropland fitted with artificial subsurface drains has also increased, reducing the capacity of the landscape to remove nitrogen.

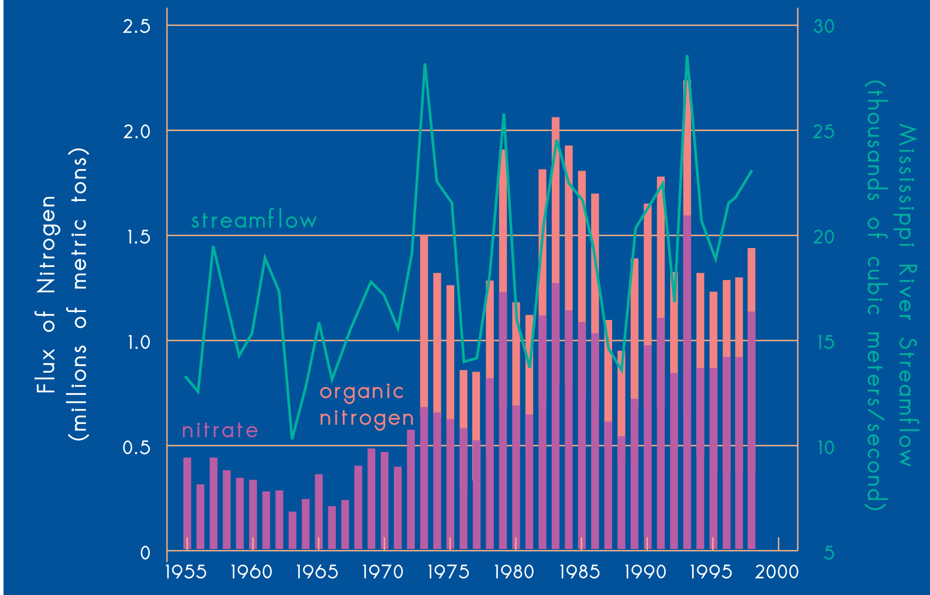
organisms and metazoans, respectively, produce carbonate shells which remain intact in buried sediments. After a transition period in the 1940s through 1950s, the diversity of these organisms decreased significantly, which is typical of stressed environments. Also, the types of organisms that remained after the transition period were those that are more tolerant of low oxygen conditions.

Long-Term Records—Drainage Basin Changes. Three key historical trends are important to consider in relationship to the above long-term trends in hypoxia. First, most of the significant flood-control and navigation channelization occurred prior to the 1950s. Second, significant alterations in the landscape (e.g., deforestation and expansion of artificial agricultural drainage) removed much of the "buffer" for runoff into the Mississippi tributaries and main stem. The greatest rates of change occurred in the 50-year period straddling the beginning of the twentieth century, with another burst in drainage development during 1945–60. Third, there was a dramatic increase in nitrogen input into the Mississippi River drainage basin, primarily from fertilizer applications, between the 1950s and 1980s. This, in turn, has led to significant increases in the flux of nitrogen from the Mississippi River system to the Gulf.

Shorter-Term Records. Extensive monitoring of the hypoxic zone did not begin until 1985, and areal estimates (see Figure 1.2) since then have been primarily from a single shelf-wide survey taken during the mid-summer of each year. Thus, for any given year, the maximum extent of hypoxia could have been significantly greater. Despite this limitation, three significant extreme events illustrate the nature of the variation in this record:

- First, during the summer of 1988, following a severe regional drought and subsequent low nitrogen load (see Figure 2.4), the hypoxic zone covered only 40 km^2 (15 sq mi), compared to 5,000–20,000 km2 (2,000–8,000 sq mi) in other years. The hypoxic zone had developed in the spring but was not maintained into the summer because of reduced flow of fresh water and resulting lack of stratification.
- Second, the size of the hypoxic zone nearly doubled during the summer following the 100-year flood of 1993.

FIG. 2.4 Annual Nitrogen Loads and Streamflow to the Gulf: 1955–98



Source: Figure 4.2 of the Topic 3 Report for the Integrated Assessment.

The annual flux of nitrate nitrogen from the Basin to the Gulf of Mexico has almost tripled between the periods 1955-70 and 1980-96. Organic nitrogen measurements were not regularly made before 1973 but show no trend. Both streamflow and nitrate flux have become much more variable in the last 25 years.

While it is not clear why this larger area has persisted in years following 1993, nitrogen recycling and resuspension of recently deposited, algal-produced organic material are likely important factors.

- Third, the year 1999 was somewhat unusual in that both streamflow and nitrate concentrations during the spring and summer were above normal in the upper Mississippi. The streamflow of the Mississippi River at Thebes, above the Ohio River confluence for January–June 1999 averaged 9,300 m^3/s, as compared with a January–June 1980–98 mean of 8,054 m^3/s. The mean nitrate concentrations for January–June 1999 were 3.4 mg/L, versus a 1980–98 mean for these months of 2.7 mg/L. However, drought conditions were developing in the upper Ohio Basin, which produced below-normal streamflow in 1999 of 10,650 m^3/s, versus a mean of 12,070 m^3/s for January–June 1980–96. Nitrate concentrations (1.2 mg/L for January–June) were near normal for this period. The combination of above-normal flows and nitrate concentrations from the upper Mississippi and below-normal flows from the Ohio River produced higher-than-normal nitrate concentrations and flux in the lower Mississippi River, and may have contributed to the record large extent of the hypoxic zone measured in July 1999.

Model Simulations

Model analyses provide further evidence connecting the extent of the hypoxic zone to river nutrient flux. Computer models have been constructed to simulate algal dynamics, nutrient cycles, sedimentation, organic carbon production and decay, and oxygen dynamics as functions of river nutrient loads and other environmental factors, such as variations in sunlight and ocean currents (Bierman et al. 1994; Justić et al. 1996, 1997). These models were designed to examine the relative effects of various factors on hypoxia, such as ocean circulation, vertical stratification, light variation, nutrient loads, and climate change. These analyses show that river nutrient load is a highly significant factor in controlling hypoxia and that rates of algal production and oxygen depletion change significantly when modeled river loads were changed.

Sources, Loads, and Trends of River Nutrients

Analyses were conducted to determine the flux and sources of nutrients transported from the Mississippi–Atchafalaya River Basin (MARB, or the Basin) to the Gulf of Mexico. These analyses aimed to identify where in the Basin the nutrients came from and to estimate the relative importance of specific human activities—such as agriculture, point-source discharges, and atmospheric emissions—in contributing nutrient flux to the Mississippi River and the Gulf.

Nutrient Trends

River-borne nutrients and water-column stratification are the major factors controlling hypoxia in the northern Gulf of Mexico. The key nutrients in this process are nitrogen, phosphorus, and silica. Of these, nitrogen is the most important nutrient leading to the production of excess algae and subsequent hypoxia in the Gulf and other marine areas (NRC 1993). Nitrogen is also the only nutrient that has increased significantly in concentration and loads in the Mississippi River in recent decades. Phosphorus loads have not changed significantly since the early 1970s when records began, and silica loads decreased between the 1950s and 1970s and have not changed significantly since then.

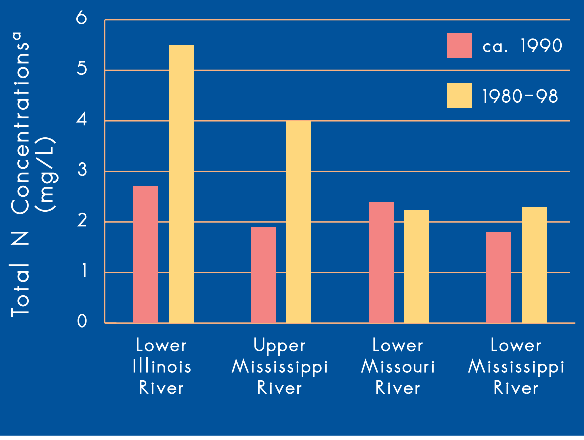
Nitrogen is present primarily in three forms in the Mississippi River and its tributaries: dissolved inorganic nitrogen (nitrate and ammonium), dissolved organic nitrogen, and particulate organic nitrogen. Total nitrogen is the sum of these three forms. For 1980–96 the average total nitrogen flux from the MARB to the Gulf was estimated to be 1,567,900 metric tons per year. Of this amount,

> Scientific investigations indicate that oxygen stress in the northern Gulf of Mexico is caused primarily by excess nutrients delivered to Gulf waters from the Mississippi–Atchafalaya River drainage basin, in combination with the stratification of Gulf waters.

Table 2.1 Historical and Recent Data on Nitrogen (N) Concentrations in the Mississippi River Basin

		Organic N			Inorganic N			
Location	**Number of Samples**	**DON**	**PON**	**Total**	**Nitrate-N**	**NH_4–N**	**DIN**	**Total N[a]**
		(milligrams per liter as N)						
Lower Illinois River								
1897–1902	weekly	0.59	0.42	1.01	1.25	0.38	1.63	2.64
1980–98	189	0.45	0.60	1.22[b]	4.09	0.14	4.23	5.46
Upper Mississippi River near Grafton (below Illinois & above Missouri Rivers)								
1899–1900	70	0.48	0.62	1.10	0.59	0.13	0.72	1.82
1980–98	120	0.81	0.63	1.27	2.63	0.11	2.74	4.01
Lower Missouri River								
1899–1900	63	0.30	1.53	1.83	0.51	0.06	0.57	2.40
1980–98	186	0.51	0.69	1.03	1.23	0.05	1.28	2.24
Lower Mississippi River								
1905–06	52	0.40[c]	0.76[d]	1.16	0.56	0.10[c]	0.66	1.82
1955–65	308	0.52[f]	0.69[g]	1.21	0.65[e]	0.10[f]	0.75	1.96
1980–98[e]	104	0.52	0.38	0.92	1.45	0.06	1.51	2.40

FIG. 2.5 Nitrogen Concentrations in the Mississippi River Basin



[a] Total nitrogen calculated as the sum of total organic N + dissolved inorganic nitrogen (DIN).

[b] Dissolved organic nitrogen (DON) and particulate organic nitrogen (PON) were not analyzed on all samples in 1980–98. Thus, DON + PON does not equal total organic nitrogen (N) for this time period.

[c] Estimated from concentrations in the upper Mississippi River and lower Missouri River.

[d] Estimated as two times the average 1980–98 PON concentration.

[e] From Table 3.4 of the Topic 3 report.

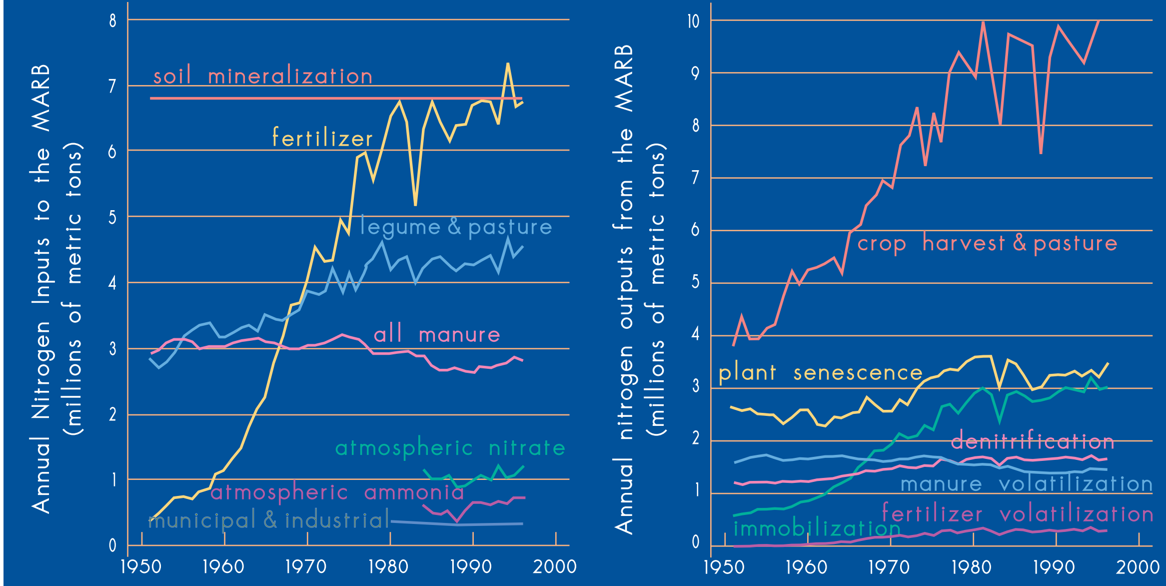
[f] Estimated.

[g] Calculated from 1955–65 daily sediment concentration at Tarbert Landing (4,018 samples; mean = 460 mg/L) and estimated sediment nitrogen content of 0.15%; PON = 0.69 +/- 0.41 mg/L.

about 63 percent was dissolved inorganic nitrogen (61 percent nitrate and 2 percent ammonium), 24 percent was dissolved organic nitrogen, and 13 percent was particulate organic nitrogen. Most of the analysis of nitrogen changes (trends) discussed in the Committee on Environment and Natural Resources hypoxia topic reports focused on nitrate, which comprises most of the dissolved inorganic nitrate. The principal reason for the focus on nitrate, rather than total nitrogen, is that nitrate is the most significant bioavailable form of nitrogen transported into the Gulf. Dissolved inorganic nitrogen concentration and flux have changed more than any other form of nitrogen and, therefore, potentially have a much larger effect on algal production and hypoxia than do dissolved and particulate organic nitrogen.

Published data (Palmer ca. 1903; Leighton 1907; and Dole 1909) from the period 1897–1906 for four locations in the MARB show that both nitrate and total nitrogen concentrations have increased significantly in the last 100 years (Table 2.1 and Figure 2.5). Mean nitrogen concentrations at these four sites for 1980–98 are also shown in the table for comparison. Concentrations of total nitrogen increased significantly at three of the four sites during the past 100 years, and essentially all of the increase can be attributed to dissolved inorganic nitrogen or nitrate. The total nitrogen concentration in the lower Mississippi is estimated to

FIG. 2.6 Annual Nitrogen Inputs to and Outputs from the Basin: 1951–96



Sources: Figures 5.7 and 5.9 of the Topic 3 Report for the Integrated Assessment.

The largest changes in nitrogen inputs to and outputs from the Mississippi Basin occurred between the 1950s and 1980s. Fertilizer nitrogen inputs increased from less than 1 million to more than 6 million metric tons per year, and crop harvest and pasture production more than doubled.

have increased by a factor of 1.3 since 1905–06, and nitrate has increased by a factor of about 2.5. Mean annual total nitrogen concentrations in the lower Illinois River and the Mississippi River at Grafton, Illinois, doubled in the last 100 years, while nitrate concentrations increased by factors of three to more than four. The exception is the lower Missouri River, where total nitrogen concentrations decreased slightly due to a large decrease in particulate organic nitrogen concentrations associated with construction of reservoirs on the Missouri River in the 1950s and 1960s. Trapping of sediment in the reservoirs has reduced the discharge of suspended sediment by more than 50 percent (Meade 1995), resulting in a similar reduction in particulate organic nitrogen. However, nitrate concentrations in the lower Missouri have more than doubled and make up for most of the decrease in particulate organic nitrogen.

The most significant trend in nutrient loads has been an increase in nitrate load, which has almost tripled from 0.33 million metric tons per year during 1955–70 to 0.95 million metric tons per year during 1980–96 (see Figure 2.4).

Figure 2.6 shows trends in annual nitrogen inputs to and outputs from the MARB. The most significant changes in both inputs and outputs occurred between the 1950s and 1980s, when fertilizer input more than tripled, and crop harvest and pasture production increased by about 2.4 times. Total nitrogen inputs increased by about 9 million metric tons per year, from about 13 million to nearly 22 million metric tons per year. Outputs increased by about 11 million metric tons per year.

The difference between these inputs and outputs (the residual) represents nitrogen potentially available as loadings to the aquatic environment (see Figure 2.7). The rapid decline in residual corresponds to the period of rapid change in fertilizer application and crop harvests and may represent increased efficiency in the use of nitrogen in crop production. Residuals since around 1980 have exhibited no trend, although they have become highly variable from year to year. The leveling off of nitrogen fertilizer, crop outputs of nitrogen, and the nitrogen residuals may indicate that a new steady-state condition was established about 1980.

Seasonal Variability

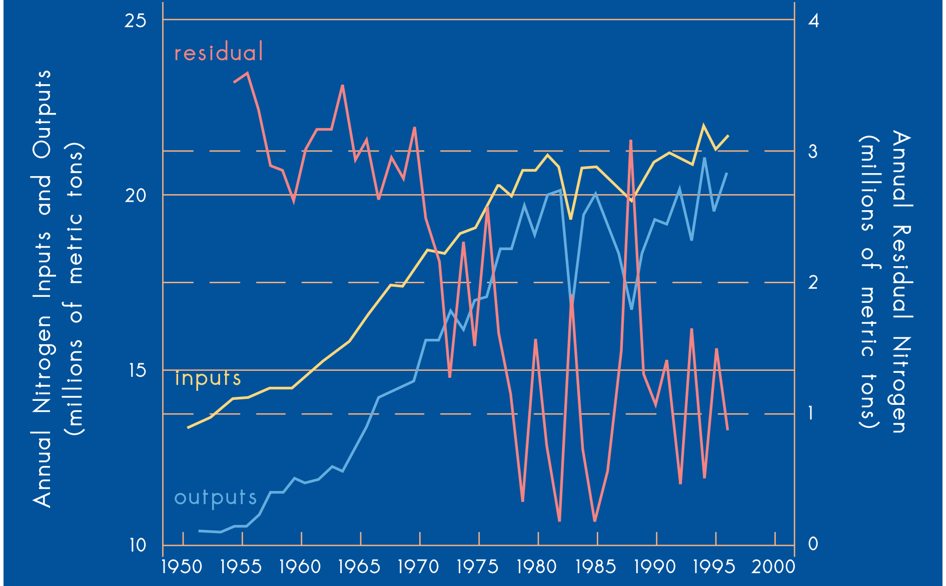
Nitrogen concentrations and loads vary seasonally. Loads and freshwater discharge are usually highest during the late winter, spring, and early summer when runoff is highest. The seasonal and annual cycles of nitrate transport are illustrated in Figure 2.8.

Precipitation leaches the highly soluble nitrate from the soil into streams via ground-water discharge, agricultural drains, and, under some conditions, overland runoff. Nitrate is subsequently transported into the Mississippi River and eventually discharges to the Gulf of Mexico.

Nitrogen Sources

The principal sources of nitrate in the MARB are river basins that

FIG. 2.7 Nitrogen Mass Balance for the Basin: 1951–96



Sources: Figure 6.4 of the Topic 3 Report for the Integrated Assessment.

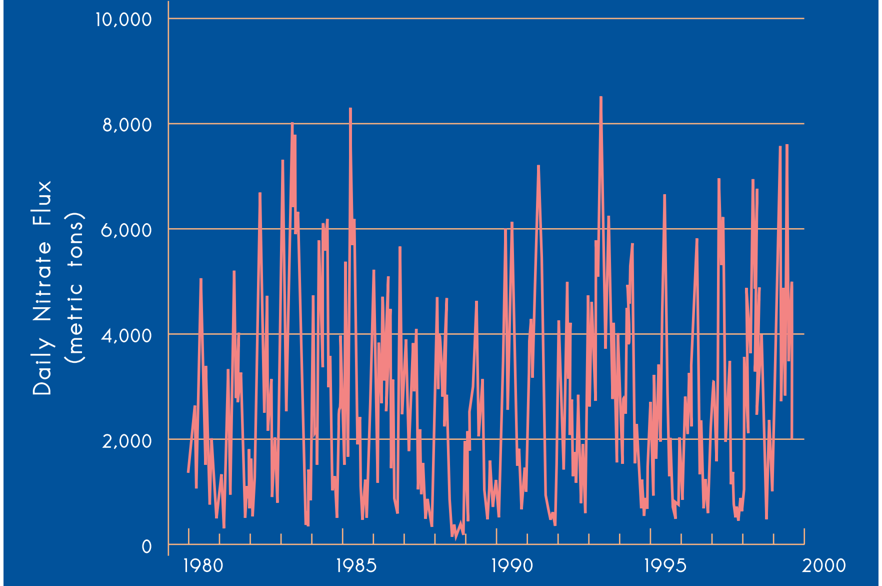
Both inputs to and outputs from the Basin have increased dramatically since about 1950. The difference between inputs and outputs—the residual—declined rapidly between 1969 and 1978, possibly indicating increased efficiency in the use of nitrogen in crop production. Essentially no change in residuals has occurred since 1980, although they have been highly variable from year to year.

drain agricultural land in southern Minnesota, Iowa, Illinois, Indiana, and Ohio (see Figure 2.9). This is an area of intensive corn and soybean production, where large amounts of nitrogen from fertilizer and manure are applied to soils every year. Legumes and atmospheric deposition add nitrogen to the soils in this region, which also contain large amounts of organic nitrogen, some of which is converted to soluble nitrate each year. The nitrate accumulated from all sources and not used by crops or removed by biogeochemical processes is subject to being leached to streams and ground water by precipitation. Extensive use of tile drains in this region can intercept water with high levels of nitrate and accelerate its transport directly to ditches and streams. In addition, in some basins sewage treatment plants and industrial sources add nitrogen directly to streams.

All of these sources contribute to the nitrogen load transported by the Mississippi River to the Gulf of Mexico. About 56 percent of the nitrate transported to the Gulf enters the Mississippi River above the Ohio River. The Ohio basin subsequently adds another 34 percent of the nitrate load.

Since 1980, the Mississippi and Atchafalaya Rivers have discharged, on average, about 1.6 million metric tons of total nitrogen to the Gulf each year; 0.95 million metric tons of that is in the form of nitrate.

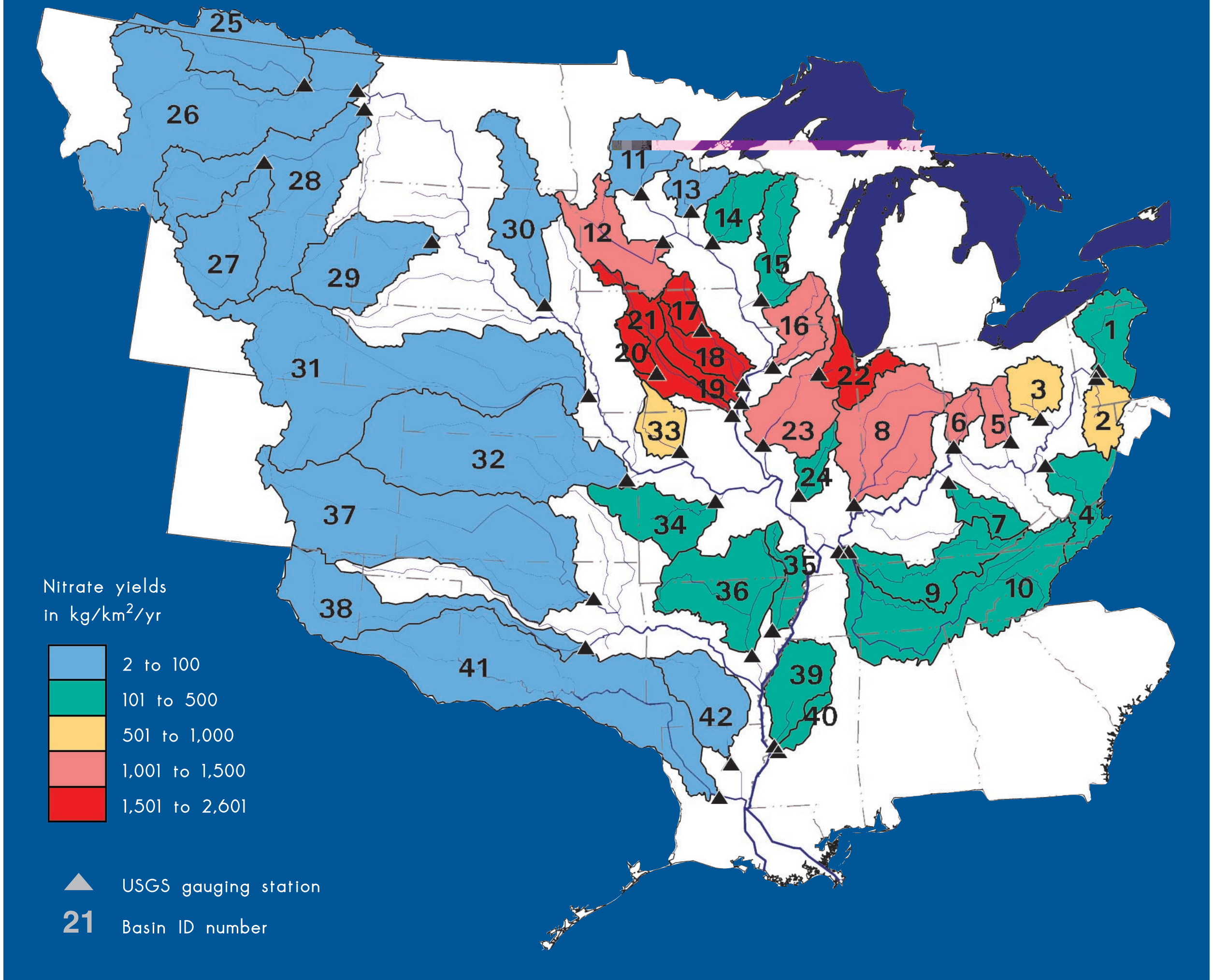
FIG. 2.8 Daily Flux of Nitrate from the Basin to the Gulf: August 1980–1999



Sources: Figure 4,1 of the Topic 3 Report for the Integrated Assessment, with an update from Donald Goolsby, U.S. Geological Survey.

The daily flux of nitrate varies from a low of several hundred metric tons per day during low streamflow in the fall to several thousand metric tons per day during high streamflow in the spring.

FIG. 2.9 Average Annual Nitrate Yields for the 42 Sub-basins within the Basin: 1980–96



Source: Figure 4.8A of the Topic 3 Report for the Integrated Assessment.

The principal sources of nitrate are river basins that drain agricultural land in southern Minnesota, Iowa, Illinois, Indiana, and Ohio, where large amounts of nitrogen are applied to corn and soybean fields.

About 90 percent of the nitrogen comes from nonpoint sources, with the remainder coming from point sources. Table 2.2 presents the estimated contributions of nitrate and total nitrogen from the predominant sources in the Basin.

Table 2.2 Estimated Contributions of Nitrogen Input Sources to the Total Nitrogen and Nitrate Nitrogen Yield of the Mississippi–Atchafalaya River Basin and Flux to the Gulf of Mexico

Source of Nitrogen Transported to the Gulf	Percent of Nitrate	Percent of Total Nitrogen
Agricultural nonpoint sources	74	65
Other nonpoint sources	16	24
Municipal and industrial point sources	9	11

The Consequenc of Hypoxia and Nutrient Over-Enrichment

The consequences of hypoxia in the Gulf of Mexico are not fully known. This chapter examines what is known about hypoxia's direct effects on fisheries and on the structure of the marine ecosystem in the Gulf. It also describes the consequences of excess nutrients—the probable primary cause of hypoxia—for water quality and ecosystem functioning within the Mississippi–Atchafalaya River Basin (MARB).

Consequences in the Gulf

The shallow continental shelf area in the Gulf of Mexico that is affected by hypoxia shows signs of hypoxia-related stress—low abundance of fish and shrimp and distinctly different benthic communities. While current ecological conditions are a response to a variety of stressors, the most obvious effects of hypoxia are that many bottom-dwelling, or benthic, organisms die; larger, long-lived species are eliminated; and productivity is shifted to nonhypoxic periods (energy pulsing).

The effects of hypoxia on fishery resources could include direct mortality of both fish and their food base, as well as such indirect effects as altered migration patterns, reduction in suitable habitats, increased susceptibility to predation and disease, and disruption of spawning and recruitment.

Trawl data from the fishery-independent SEAMAP database showed a very consistent pattern that whenever dissolved oxygen approached 1–3 mg/l, catch of shrimp and fish rapidly declined to zero. Laboratory experiments have shown that both white and brown shrimp are able to detect and attempt to avoid hypoxic waters. Both abundance and biomass of fish and shrimp are significantly lower where bottom-water concentrations of oxygen decline below 2 mg/l. Geographic comparisons of the distribution of fishing effort around the Gulf show that the industry has shifted shrimping efforts away from hypoxic zones (Downing et al. 1999).

Overall, fisheries landings statistics for at least the last few decades have been relatively constant. However, the brown shrimp catch—the most important commercial fishery (by dollar value) in the Gulf—declined from a record high in 1990 to below average during 1992–97, coinciding with years of greatly increased hypoxia (see Figure 3.1). Catch per unit effort for brown shrimp, while variable, has trended down since the late 1970s. Near-shore zones, away from hypoxic waters, are the usual habitat for white shrimp, which have not shown as great a decline.

An economic analysis sought to examine the relationship between the estimates of the hypoxic area and available fisheries data, primarily on the two main shrimp species in the Gulf

because they are part of the benthic community and are commercially important. Since data on the area of the hypoxic zone are only single annual estimates and are not available before 1985, the time series was judged too short to establish a credible relationship, and the analysis resorted to an extrapolation back to 1960 (see the Topic 2 report, pp. 7–8, for details). Fisheries variables examined included catch per unit effort, depth of landings, and shrimp size. This economic assessment based on fisheries data failed to detect effects attributable to hypoxia (i.e., correlations between the extrapolated time series and fisheries data were below levels usually considered statistically significant). However, this failure does not necessarily mean that hypoxic effects are absent; it only means that the data available for analysis were inadequate to identify the reasons for variability.

The shallow continental shelf area in the Gulf shows signs of hypoxia–related stress—low abundance of fish and shrimp and distinctly different benthic communities.

Fisheries data are highly variable and affected by many factors. Fisheries productivity, particularly in pelagic (or near-surface) species, may increase as a result of nutrient enrichment, but enrichment can fuel bottom hypoxia, thereby decreasing the productivity of benthic (or bottom-dwelling) species. In the food web, the documented responses of zooplankton to hypoxia include direct mortality, avoidance behavior in adults, interference with vertical migration, and changes in species composition toward smaller species that carry their eggs. Copepods, the dominant zooplankton in the northern Gulf of Mexico, are lower in abundance or absent when dissolved oxygen is less than 1 mg/l.

Comparison of benthic communities in the area affected by hypoxia with those unaffected in nearby Mississippi Sound reveals distinct differences. On the Louisiana continental shelf, benthic communities consist of disturbance-adapted populations. In contrast, the Mississippi Sound contains more fully developed, late-successional stage, "equilibrium"-type communities.

In addition to destroying bottom and near-bottom habitat, hypoxia alters energy flows in the ecosystem. During hypoxia, significant amounts of the system's energy are diverted from invertebrates to microbial decomposition. Energy flows through the ecosystem in pulses, favoring opportunistic species with shorter life cycles that can take advantage of the abbreviated time bottom habitats are available. A reduction in overall biodiversity, abundance, and biomass of the ecosystem is associated with pulsed energy systems, since longer-lived species tend to be eliminated.

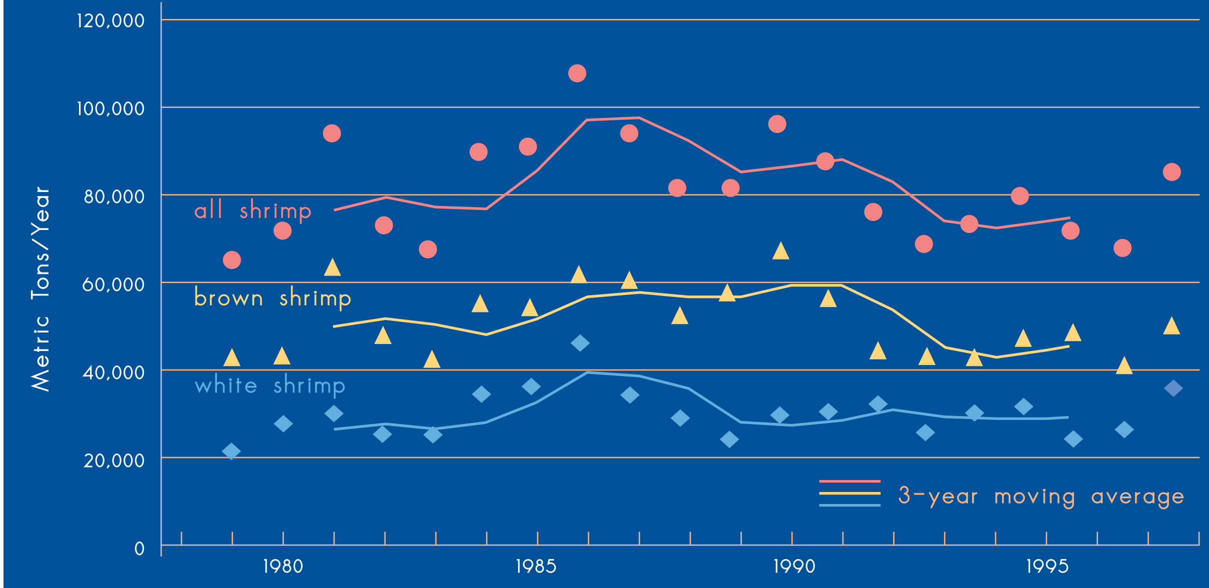
Consequences in the Mississippi–Atchafalaya River Basin

Nutrient concentrations affect many aspects of ecosystem and water quality in the Basin, including plankton composition and production, nuisance algal blooms, macrophyte communities and fish communities, as well as the suitability of waters for swimming and drinking and, ultimately, may lead to violations of water quality standards.

Review of state assessments submitted to the U.S. Environmental Protection Agency under section 305b of the Clean Water Act indicates that most states in the MARB have substantial numbers of river miles impaired by high nutrient conditions. This means that those areas are not fully supporting one or more resource uses, including aquatic life, fish consumption, and swimming. Elevated nutrient concentrations, primarily nitrogen and phosphorus, can result in excessive growth of algae and other nuisance aquatic plants, disrupting the ecological balance, clogging pipes, and interfering with recreational activities. Subsequent decay of algae can result in foul odors, bad taste, and further ecological disruption through oxygen depletion.

Legally binding numeric standards have not been established in any state for nutrients in flowing- water systems or lakes, but efforts have been directed toward the development of such standards for many years. At present, many states have a non-numeric (narrative) standard that in essence says nutrients must not be

FIG. 3.1 Trends in Annual Shrimp Yield: 1979–98



Source: NOAA National Marine Fisheries Service, www.sf.nmfs.gov/st1/commercial/landings/index.html

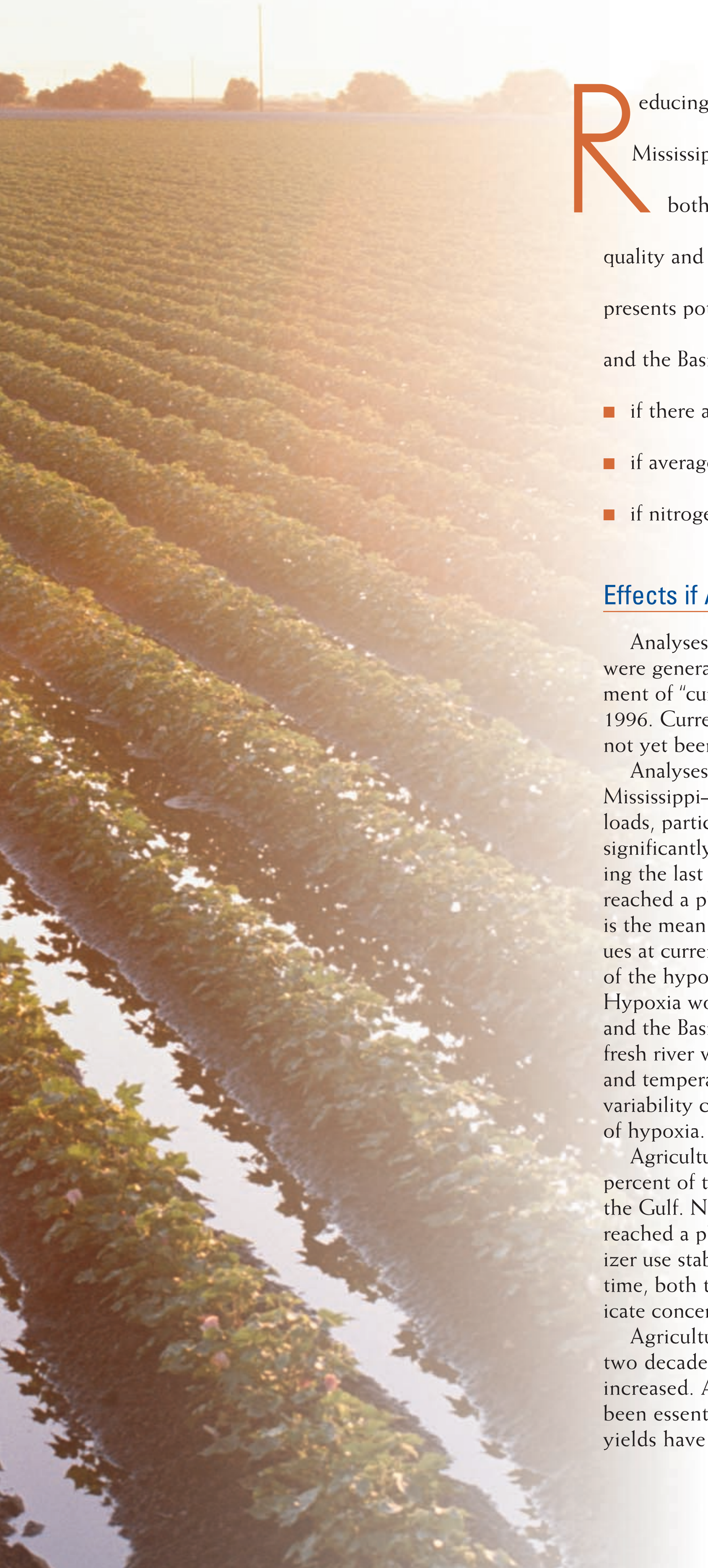
While variable, catch per unit of effort for brown shrimp off Louisiana and Texas has trended down since the late 1970s. In contrast, white shrimp haven't shown as great a decline, perhaps because they inhabit near-shore zones away from hypoxic waters.

added to a water body to the extent that they cause an imbalance in the natural flora and fauna. Although science-based numerical criteria for nutrient concentrations to classify lake ecosystems according to trophic state have been available for many years, few classification methods exist in the literature to evaluate the trophic status of stream ecosystems in quantitative terms. One simple classification scheme developed by researchers (Dodds et al. 1998) for streams would use nutrient concentrations at the boundary approximately defining mesotrophic and eutrophic conditions, which is 1.5 mg/l for total nitrogen and 0.075 mg/l for total phosphorus. Under this scheme, about 30–55 percent of the hydrologic cataloging units (HCUs) of the Ohio, Lower Mississippi, and Tennessee subbasins exceed this eutrophic threshold boundary for total phosphorus in flowing waters, and 16–40 percent of the HCUs in these regions exceed the threshold for total nitrogen in flowing waters. Higher exceedance frequencies were found in the Missouri, Upper Mississippi, and Arkansas–Red sub-basins (~80 percent of the HCUs for total phosphorus and 70–75 percent for total nitrogen) (see the Topic 4 report for details).

Excessive nitrate in drinking water can result in "blue baby syndrome" (methemoglobinemia), which causes oxygen levels in the blood of infants to be low—sometimes fatally. About 15 percent of all shallow ground water beneath agricultural and urban areas that has been sampled by the U.S. Geological Survey exceeded the 10 mg/l drinking-water standard for nitrate (USGS 1999). Contamination of shallow ground water may be a warning to alert populations to potential future risks from consumption of water from deeper wells in these aquifers.

The Effects

of Changing Nutrient Loads



Reducing nutrient loads, particularly nitrogen from the Mississippi–Atchafalaya River Basin, will cause improvements both in the hypoxic conditions in the Gulf and in water quality and land-use conditions within the Basin. This chapter presents potential effects over the next 10–20 years, in the Gulf and the Basin:

- if there are no major changes in average nitrogen loads,
- if average nitrogen loads increase, and
- if nitrogen loads are reduced.

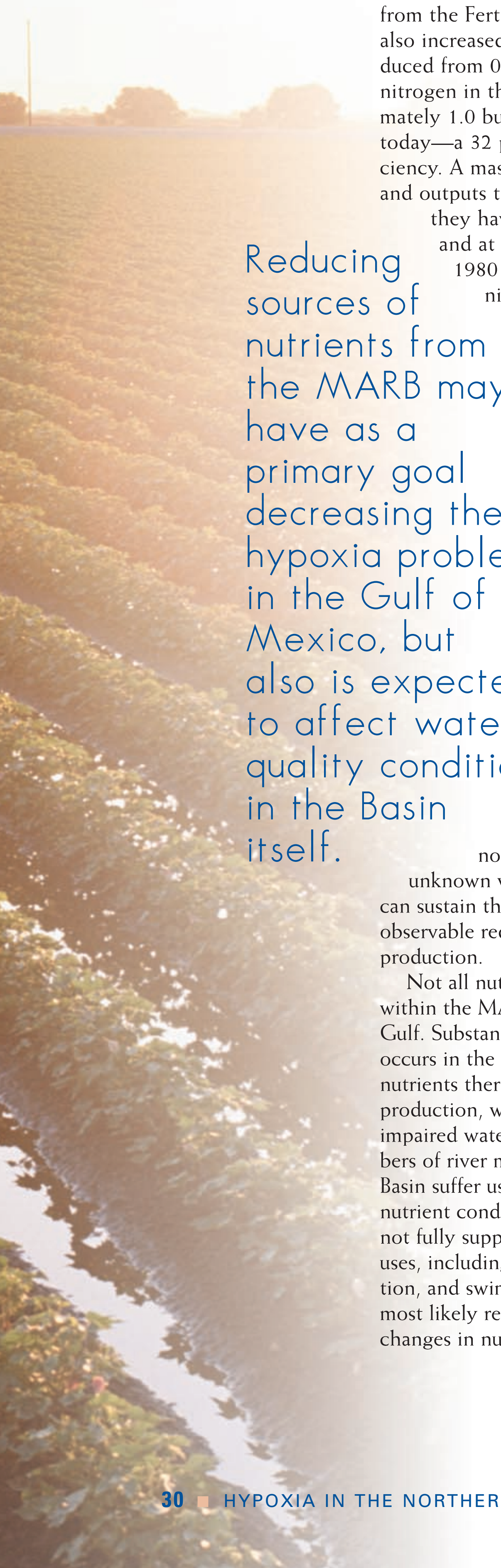
Effects if Average Loads Are Unchanged

Analyses supporting this assessment were based on data that were generally complete through the mid-1990s. Thus, the assessment of "current" activities is up to date only to about 1995 or 1996. Current activities may be having effects for which data have not yet been assessed.

Analyses presented previously in this assessment show that Mississippi–Atchafalaya River Basin nutrient concentrations and loads, particularly nitrogen, to the northern Gulf of Mexico have significantly increased over the twentieth century, especially during the last four decades. However, nitrogen loads appear to have reached a plateau of about 1.6 million metric tons per year, which is the mean load over the period 1980–96. If nitrogen flux continues at current levels, the present range of dimensions and severity of the hypoxic zone on the Louisiana shelf may be maintained. Hypoxia would vary, depending on physical factors in the Gulf and the Basin, such as spring and summer stratification caused by fresh river water flowing over marine waters, weather patterns, and temperature. However, even under these conditions, natural variability could produce new extremes of the extent and severity of hypoxia.

Agricultural nonpoint sources in the MARB constitute about 65 percent of the nitrogen and about 74 percent of the nitrate load to the Gulf. Nitrogen fertilizer use in the MARB appears to have reached a plateau beginning in the 1980s, while phosphorus fertilizer use stabilized in 1980 and then dropped slightly. At the same time, both the rise in river nitrate concentration and the fall in silicate concentration ceased.

Agricultural policies and practices have changed over the last two decades so that both crop production and efficiency have increased. Average fertilizer use per acre of corn in the U.S. has been essentially constant since the late 1970s; however, corn yields have continued to climb, resulting in an increase in the



bushels of corn produced per unit of fertilizer applied. According to comments from the Fertilizer Institute, farmers have also increased the amount of grain produced from 0.76 bushel per pound of nitrogen in the late 1970s to approximately 1.0 bushel per pound of nitrogen today—a 32 percent increase in efficiency. A mass balance of nitrogen inputs and outputs to the MARB indicates that they have been approximately equal and at a steady state since about 1980 and suggests that levels of nitrogen stored in the Basin ecosystem are no longer increasing as they did between 1955 and 1980 (see Figure 4.1).

> Reducing sources of nutrients from the MARB may have as a primary goal decreasing the hypoxia problem in the Gulf of Mexico, but also is expected to affect water quality conditions in the Basin itself.

If there are no major changes in average nitrogen loads and the Gulf of Mexico continues to experience a large zone of hypoxia each summer, the area affected is expected to continue to suffer from annual losses of biodiversity, abundance, and biomass. The loss of harvest from the hypoxic region may, or may not, be offset by harvests from nonhypoxic waters. It is unknown whether the northern Gulf can sustain this level of impact without observable reductions in overall fisheries production.

Not all nutrients entering tributaries within the MARB are transported to the Gulf. Substantial processing of nutrients occurs in the rivers and streams. Excess nutrients there can overstimulate primary production, which commonly leads to impaired water quality. Substantial numbers of river miles in most states in the Basin suffer use impairment related to nutrient conditions, meaning that they do not fully support one or more resource uses, including aquatic life, fish consumption, and swimming. This situation would most likely remain the same without some changes in nutrient loading.

Effects if Average Loads Increase

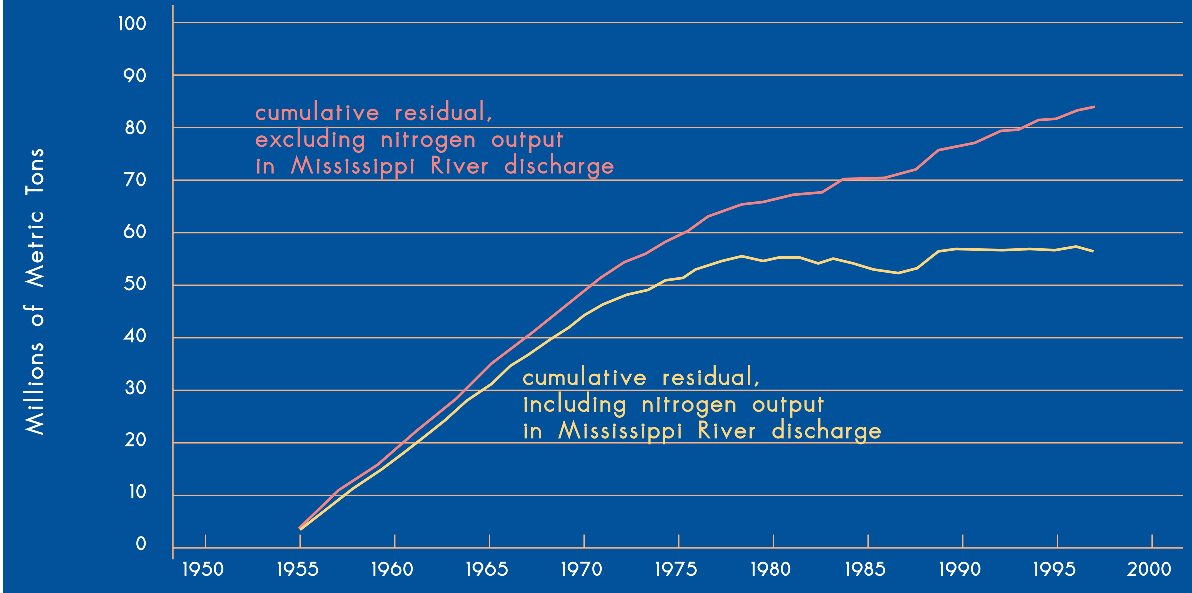
Average nitrogen loads can increase because of anticipated growth in population, food production, and fertilizer use. Changes in climate may also tend to exacerbate hypoxia in the Gulf. Increases in average nitrogen load might be offset by changes that tend to mitigate hypoxia, such as ongoing improvements in farming practices, better targeting of riparian and wetland restoration, and improved river-flow management.

Current pressures that drive hypoxic conditions are likely to intensify. U.S. population and food demand are projected to continue to grow. Over the past decade, the U.S. population has increased by 10 percent (Bureau of the Census 1999); middle series projections predict an 8 percent increase by 2010 and a 17 percent increase by 2020. World population is expected to grow at 1.2 percent per year through 2010 according to the World Bank, and the U.S. has provided a large percentage of the world's food, particularly grain.

The northern Gulf of Mexico is a coastal area that may experience increased freshwater runoff or greater extremes of influx as a result of global climate change. Streamflow was approximately 30 percent higher during 1980–96 than during 1955–70. Part of this increase may be due to long-term climatic variation, and part may be driven by shorter-term climatic cycles. The higher flows in the later half of the twentieth century are attributed to increased precipitation throughout the year and, in particular, to warmer, wetter springs. During this same period, streamflow has increased 30 percent, while nitrate flux has increased 300 percent.

Higher precipitation and streamflow as occurred in the later half of the twentieth century could influence nitrate flux in several ways. More nitrate would be transported with the larger volume of flow unless concentrations decreased more readily than flow volume increased. The higher precipitation could leach more accumulated nitrate from soils in the basin into tile drains and ditches, resulting in higher nitrate concentrations in streams. Higher streamflow would decrease the residence time of water in the river, reducing the rates of denitrification, burial, and uptake by aquatic plants and riparian vegetation.

FIG. 4.1 Cumulative Residual from Nitrogen Mass Balance: 1955–97



Source: Figure 6.4B of the Topic 3 Report for the Integrated Assessment.

Nitrogen inputs to and outputs from the Basin have been approximately equal since about 1980, and the residuals (difference between inputs and outputs) have been variable. The cumulative residual is at a steady state, indicating that levels of nitrogen stored in the Basin are no longer increasing as they did between 1955 and 1980.

The resulting higher runoff in summer would most likely affect water column stability, surface productivity, and oxygen cycling, leading perhaps to an expanded extent of the hypoxic zone.

Understanding the effects of hypoxia in other areas of the world could be useful in projecting effects in the Gulf of Mexico. Experience with other hypoxic zones around the globe shows that initially the higher nutrient concentrations lead to increased production of both organic matter and fisheries (see Figure 4.2). However, as organic matter production increases, changes occur in the food web that lead to both the ecological and the fisheries effects becoming progressively more severe as hypoxia worsens. These changes have been observed in marine ecosystems around the globe, resulting in serious ecological and economic consequences from hypoxia.

Most notable among these affected marine systems are the Kattegat, the Baltic and Adriatic Seas, and the northwestern shelf of the Black Sea. The consequences range from localized loss of target fish catch and recruitment failure (low numbers joining a population, generally due to low reproduction rates) to complete system-wide loss of fishery species. Where oxygen depletion is severe, the food web that supports bottom feeders, such as shrimp and drum, is disrupted, as well as the natural processing of organic matter, nutrients, and pollutants.

In the Gulf of Mexico region, Louisiana leads in production and landings of commercial and recreational marine fisheries. The fishery resources of the Gulf are among the most valuable in the United States, generating $2.8 billion annually. Although possibly due to factors other than hypoxia, catch per unit of effort for brown shrimp, one of the most commercially valuable species in the Gulf, has trended down since the late 1970s.

Other areas that have experienced severe hypoxia, with near-anoxic conditions, experienced greater mortality and had fewer species and lower biomass than areas with intermittent or less severe hypoxia. If experiences in other coastal and marine systems are applicable to the Gulf of Mexico, then the potential impact of worsening hypoxic conditions could be the decline (perhaps precipitous) of ecologically and commercially important fisheries.

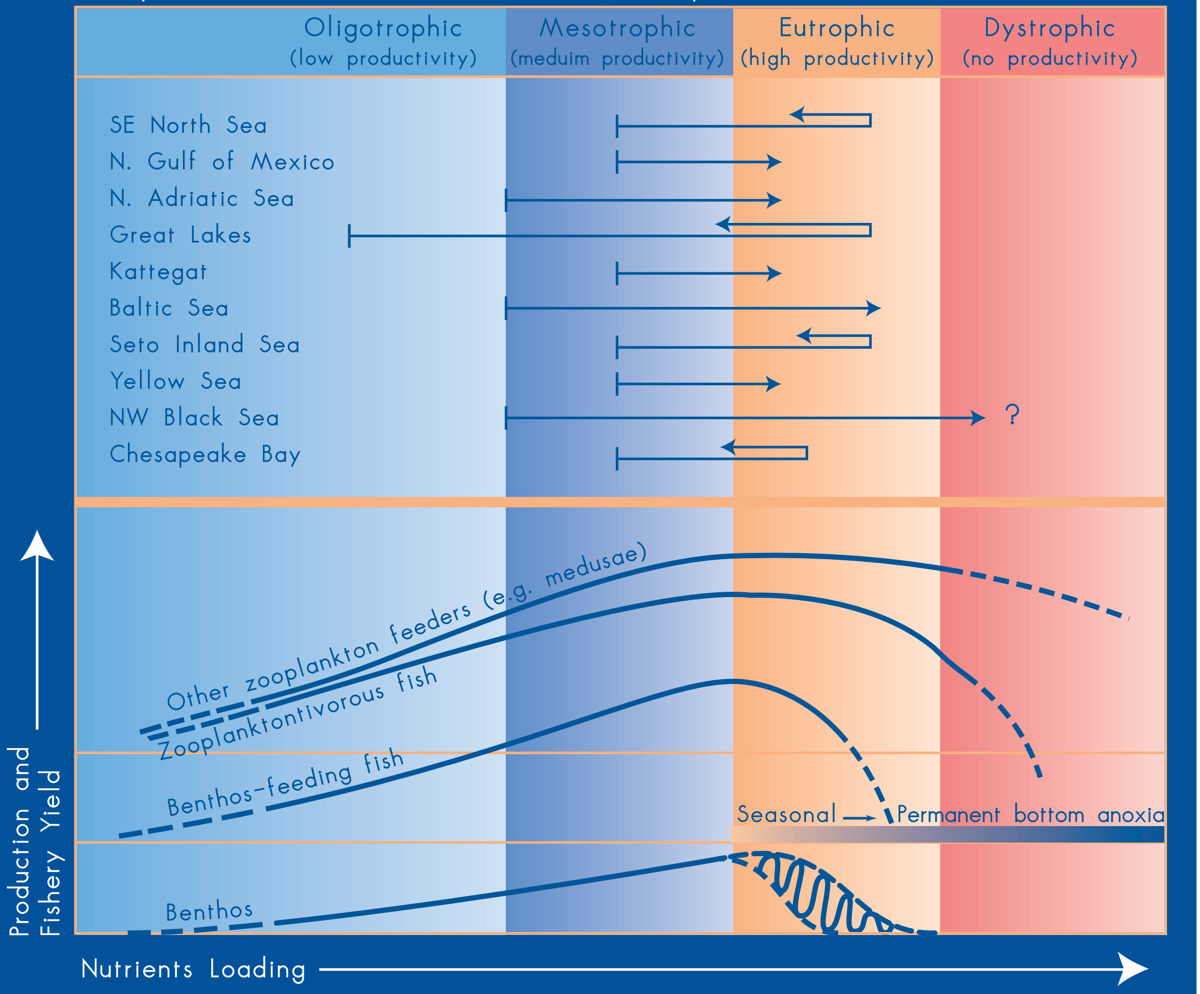
The degree of ecological and economic effects related to hypoxia varies from system to system. For example, both ecological and economic effects of the combined problems of eutrophication and hypoxia have been seen in the Black and Baltic Seas, where demersal trawl fisheries have been either eliminated or severely stressed. Initially in the Kattegat, hypoxia caused mass mortality of commercial and noncommercial species. Now large-scale migrations and/or mortality among demersal fish and the Norway lobster (*Nephrops*) continue, resulting in a changed species composition and reduced growth and biomass. Hypoxia in the Kattegat is believed to be partly responsible for the overall decline in stock size, recruitment, and landings of commercial fish over the last two decades.

Louisiana's commercial and recreational fisheries depend on species that spend part of their life cycles within shallow continental shelf waters that often overlap the hypoxic zone. This is true not only for shrimp but also for the benthic organisms that form the forage base for valuable commercial and recreational species. Because shrimp must move from inshore wetland nurseries to offshore feeding and spawning grounds, hypoxia can block their migration. Spawning grounds, migratory pathways, feeding habitats, and fishing grounds of important species are affected by the extent and severity of hypoxic waters. Expansion of the hypoxic zone could lead to further decreases in productivity at higher levels of the food web and loss of essential habitats.

Increasing nitrogen loads have decreased the silica-to-nitrogen ratio. Decreased silica availability in relation to increasing availability of other nutrients could stimulate blooms of harmful algae, such as dinoflagellates. *Pseudo-nitzschia* spp., a group of diatoms, including some toxic forms, that require silica, have increased in abundance in spite of silica decreases, most likely in response to increasing nitrogen inputs from the Mississippi River.

Although higher nutrient concentrations initially increase the productivity of fisheries, ecological systems worldwide show negative effects as nutrient loading increases and hypoxic or anoxic conditions develop. Each generic curve in the lower half of the figure represents the reaction of a species guild to increasing nutrient supplies. The top half of the figure illustrates trends in various marine systems around the world. Reversals show that trends toward over-enrichment have been turned around in several areas.

FIG. 4.2 Comparative Evaluation of Fishery Response to Nutrients



Source: Redrawn from Caddy 1993.

Effects if Average Loads Are Reduced

Reducing sources of nutrients from the MARB may have as a primary goal decreasing the hypoxia problem in the Gulf of Mexico but also is expected to affect water quality conditions in the Basin itself. Although there are distinct differences between the nature of the responses to such reductions in the two systems, not surprisingly, there are also substantial similarities. In both the Gulf and the Basin, response variables of interest include various nutrient forms, chlorophyll, dissolved oxygen, water clarity, planktonic and benthic biota, and higher organisms. However, the response variable of primary interest for hypoxia is dissolved oxygen in the bottom waters of the Gulf of Mexico.

Depending on the suite of techniques used to reduce loads (i.e., the mix of source reductions, wetland restoration, and river management), a number of costs would be incurred, including those associated with higher material, equipment, and management costs of improved farming practices; loss of productive farmland; and increased treatment costs for municipalities and industry (air and wastewater controls). In addition to reducing risks of precipitous decline in Gulf fisheries from hypoxic/anoxic conditions, these costs would be offset by a number of benefits within the Basin, including improved water and habitat quality, reduced soil erosion, reduced contamination of drinking-water sources by nitrates, improved water quality for recreational use, improved recreational fisheries and wildlife, cost-effective flood damage reduction, and restoration of critical coastal wetlands in Louisiana.

Changes in the Gulf of Mexico

Simulations with a quantitative water quality model (Bierman et al. 1994) indicate that dissolved oxygen and chlorophyll concentrations on the Louisiana continental shelf are likely to be responsive to reductions in nutrient loads from the MARB. However, there are large uncertainties in the magnitudes of these responses for a given load reduction. For nutrient load reductions of 20–30 percent, bottom-water dissolved oxygen concentrations were estimated to increase by 15–50 percent, and surface chlorophyll concentrations were estimated to decrease by 5–10 percent. The ranges correspond to different assumptions for sediment responses and large-scale Gulf of Mexico water quality, and to different hydrometeorological conditions among different years. Although both nitrogen and phosphorus load reductions produced responses in the model, the response, particularly for dissolved oxygen, was somewhat greater for nitrogen reductions.

There has been no statistically significant long-term trend in phosphorus flux to the Gulf for

Thousands of small shrimp boats trawl the northern Gulf of Mexico. Important commercial species in the Gulf, such as shrimp, avoid hypoxic areas, where they would otherwise spend part of their life cycle. Benthic organisms that provide food for other sought-after species are also disrupted in the hypoxic zone.


NOAA NATIONAL MARINE FISHERIES SERVICE

the period 1972–96. Over the past half century, phosphorus flux, a large portion of which is associated with sediments, has probably decreased. Nitrogen is the only component of nutrient flux that has increased. For nitrogen load reductions of 30–50 percent (returning to the levels that existed in 1955–70), the model estimates that dissolved oxygen concentrations would increase by 20–75 percent.

There appears to be no evidence that the ecological changes related to hypoxia in the northern Gulf of Mexico at this point are irreversible. Experience has demonstrated that ecosystems can respond positively to nutrient reductions. Examples include Chesapeake, Tampa, and Sarasota Bays. Reductions in loads to Tampa Bay are attributed to improvements in wastewater treatment and in fertilizer loading operations in the Port of Tampa. In Sarasota Bay, reductions occurred as a result of improvements in wastewater treatment and agricultural re-use, and the use of deep-injection wells for wet-weather effluent disposal (Johansson and Greening 1999). There are many examples of small-scale hypoxia reversals associated with improvements in treatment of sewage and pulp mill effluents. In the U.S., the improved water quality in Lake Erie is a good example of positive response to nutrient reductions but is also a demonstration that the time interval for achieving noticeable improvements may be long—on the order of five to ten years after nutrients are reduced. Substantial nutrient reduction targets are being proposed for the drainage area of the Baltic Sea in order to control eutrophication (Jansson and Dahlberg 1999).

Public water supplies are treated, if necessary, to ensure that nitrate levels are below the drinking-water standard of 10 mg/l. People drinking ground water from shallow wells in vulnerable geologic settings (sand, gravel, or karst) in rural agricultural areas, however, are exposed to risks that could be reduced through reductions in nitrogen loading.

KEVIN F. DENNEHY, U.S. GEOLOGICAL SURVEY

Changes in the Watershed

The most direct effect of actions to reduce nutrient loading to surface waters in the MARB will be to decrease concentrations and to shift the composition of nutrients in its rivers and streams. The changes in nutrient concentrations and composition will induce other changes in trophic conditions and should result in Basin-wide improvements in surface-water quality. The extent of reductions achieved (and subsequently the effects) will depend on site-specific characteristics (climate, soils, cropping history), the types of improvements in management, and the baseline conditions to which the management improvements are being compared.

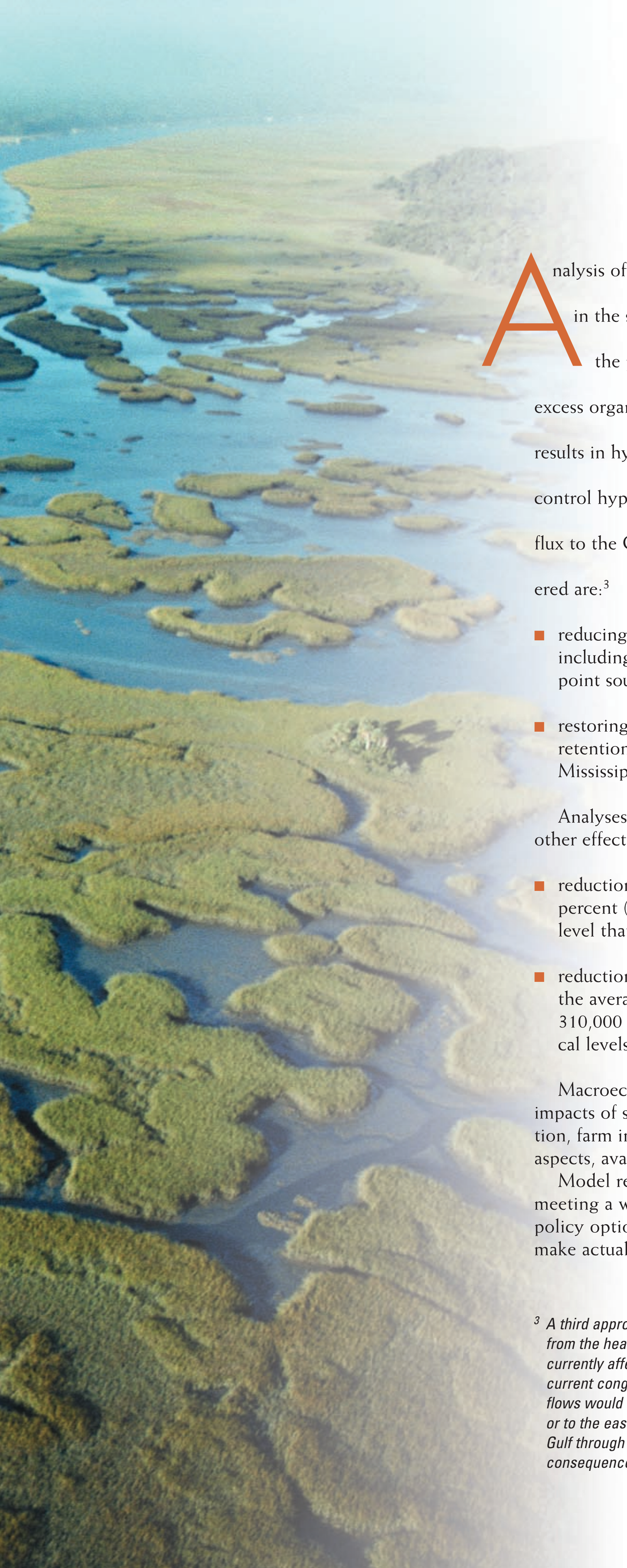
Aquatic macrophytes (such as duckweed, water lilies, and sedges) have important effects on water quality in shallow waters throughout the Basin. If reductions in nitrogen and phosphorus levels cause an increase in underwater light, submerged aquatic macrophyte distribution would be expected to expand in the upper Mississippi River. The effects on water quality will be beneficial, both locally and system-wide. Increased macrophyte abundance may enhance nutrient retention significantly, leading to lower delivery rates of nutrients to the Gulf of Mexico than would otherwise be predicted for direct effects of source reductions.

Reductions in nutrient concentrations would not be expected to strongly affect sport fisheries because the rivers and streams in the Basin would most likely continue to be highly productive systems. Any decline that might occur in total biomass production would likely be more than offset by habitat and other improvements that would promote game fish over rough fish populations.

All the nutrient-reduction approaches considered—including steps to reduce nutrient losses from farmlands, reduce nutrient discharges from point sources, and increase natural processes to remove excess nutrients from surface waters—are expected to produce environmental benefits within the Basin. These include the values associated with restored wetlands, reduced soil erosion, reduced nitrogen contamination of drinking water, reduced vulnerability to floods, better wildlife habitat, and improved recreational water quality. Other potential benefits of nutrient-reduction activities include more efficient use of organic and inorganic fertilizers and the energy associated with them, lower overall fertilizer costs, decreased health risk from contamination of public and private drinking-water supplies, and improved aquatic habitat in streams, lakes, rivers, and estuaries. All the approaches considered will also have associated costs, including costs for changes in land use; introduction of new technologies, such as precision agriculture and biological nitrogen removal; and implementation of improved management practices. The estimated economic costs of the various approaches to reduce nutrients are described in the next chapter.

Approaches

for Reducing Nutrient Loads



Analysis of the causes of hypoxia in the Gulf of Mexico, as noted in the second chapter of this report, indicates that nitrogen is the principal nutrient fueling production and deposition of excess organic matter which, when stratified conditions exist, results in hypoxia. Thus, the approaches to reduce, mitigate, and control hypoxia in the Gulf of Mexico focus on reducing nitrogen flux to the Gulf. The two primary approaches that can be considered are:[3]

- reducing nitrogen loads to rivers and streams in the Basin, including losses of nitrogen from farmlands and loads from point sources, atmospheric deposition, and other sources; and
- restoring and enhancing natural denitrification and nitrogen-retention processes to reduce nitrogen loads from the Mississippi and Atchafalaya Rivers to the Gulf.

Analyses of these approaches examined the economic and other effects of achieving nitrogen load reductions at two levels:

- reduction of total nitrogen loads to the Gulf of Mexico by 40 percent (approximately 625,000 metric tons/yr), to the average level that existed during 1955–70; and
- reduction of nitrogen loads by approximately 20 percent from the average level of the 1980–96 period (approximately 310,000 metric tons/yr), midway between reduction to historical levels and no reduction.

Macroeconomic models were used to evaluate system-wide impacts of some broad policy approaches on agricultural production, farm income, consumer prices, and the like. For many aspects, available models offer only rough approximations.

Model results report the broad economic consequences of meeting a water quality goal and are useful for comparing broad policy options. However, the model results cannot be used to make actual policy recommendations for any particular area in

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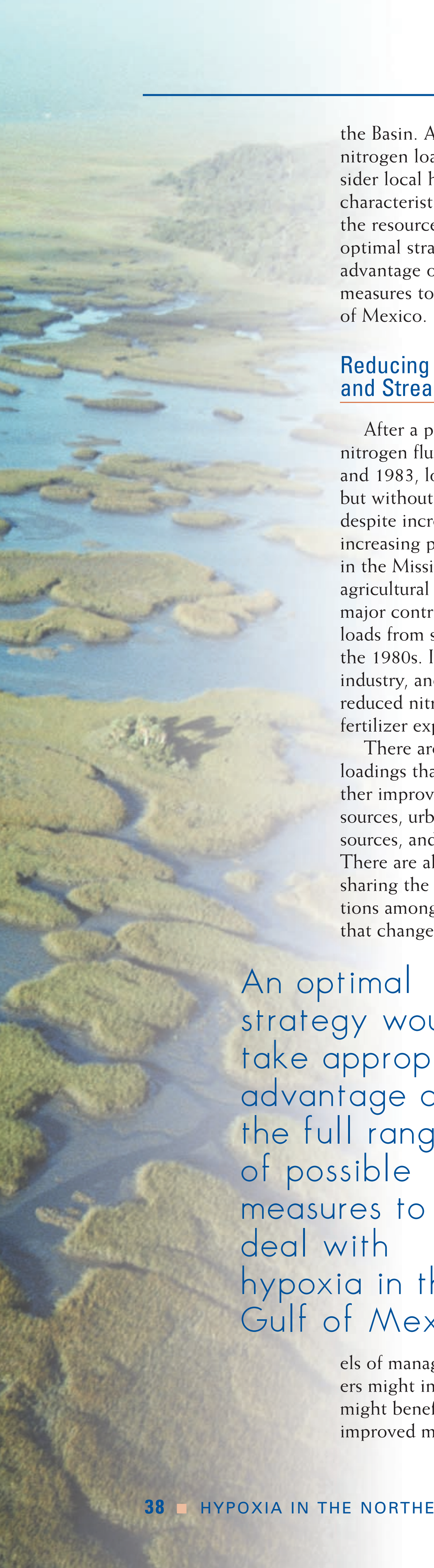
[3] *A third approach, recently raised, calls for diverting nutrient-laden waters away from the heart of the hypoxic zone in the central Gulf to areas that are not currently affected by hypoxia. To do this would require an alteration of the current congressionally mandated 70/30 flow split at Old River, so that additional flows would be passed into the Gulf by the main channel of the Mississippi River, or to the east side of the "Bird Foot Delta," while reduced flows would enter the Gulf through the Atchafalaya River distributary. This option would have multiple consequences and has not been analyzed.*



the Basin. Any program for reducing nitrogen loading to the Gulf should consider local hydrologic conditions and the characteristics of agricultural production, the resource base, and the producers. An optimal strategy would take appropriate advantage of the full range of possible measures to deal with hypoxia in the Gulf of Mexico.

Reducing Nitrogen Loads to Rivers and Streams in the Basin

After a period of marked increase in nitrogen flux to the Gulf between 1970 and 1983, loads have remained variable but without statistically significant trends, despite increasing agricultural production, increasing population, and other pressures in the Mississippi River Basin. Improved agricultural practices are probably the major contributors to keeping nitrogen loads from significantly increasing since the 1980s. Innovations by researchers, industry, and individual farmers have reduced nitrogen losses, in part to reduce fertilizer expenditures.

There are several sources of nutrient loadings that might be targeted for further improvement, including agricultural sources, urban point and nonpoint sources, and atmospheric deposition. There are also several possible options for sharing the burden of nutrient load reductions among all sectors. Analyses suggest that changes in agricultural practices to achieve modest levels of nutrient reduction can provide the least-cost option to society overall while maintaining high levels of production and realizing relatively minor impacts on net farm income sector-wide. However, because different agricultural regions and individual crops are more sensitive to changes in nutrient levels and because producers have different levels of management skills, specific producers might incur severe costs, while others might benefit from reduced costs due to improved management practices.

An optimal strategy would take appropriate advantage of the full range of possible measures to deal with hypoxia in the Gulf of Mexico.

Ultimately, there are many questions about how these improved practices would be motivated and how the costs would be borne. Differing implementation strategies could impose costs primarily on agricultural producers, consumers, or—if these costs are supported through incentive payments—society at large. How to pursue effective implementation of a solution to Gulf hypoxia across the different nutrient sources and a multitude of state and federal water quality laws and programs will require consideration of a broader range of factors than was attempted in this assessment.

Some reduction in nitrogen loads from municipalities could be achieved by the elimination of combined sewer overflows and the installation of biological nutrient control processes in new sewage treatment plants. While such sources are not the major contributor to the total nitrogen load from the Basin, they discharge directly to major streams, with little opportunity for natural treatment.

Discharges of nitrogen from farms to streams and rivers could be reduced by implementing a wide variety of changes in management practices, such as:

- applying nitrogen fertilizer and manure at not more than agronomically recommended rates;
- switching from fall to spring application of fertilizer;
- improving management of livestock manures, whether stored or applied to the land;
- changing from row-cropping to perennial-cropping systems;
- planting cover crops for fall and winter nutrient absorption;
- switching from conventional to ridge-tilling or other reduced-tillage practices;
- ensuring that the lateral spacing of subsurface tile drainage is not less than 15 meters;
- controlling water tables to promote denitrification within the soil column; and

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The spatial pattern of the manure input to the Basin has changed from a highly dispersed to a highly concentrated distribution as confined animal feedlot operations, such as shown here, have become more common. Improving management practices for storage and application can reduce nitrogen losses to streams and rivers.

- routing soil drainage effluent through wetlands, grass buffer strips, or riparian forest buffers.

Nitrification inhibitors for fertilizers, amino acid feed supplements, and other measures have also been suggested. For some of the above improved management practices, reduction in nitrogen losses to streams are on the order of 10–20 percent of baseline conditions, but others have been shown to reduce losses by as much as 90 percent in specific field studies (see the Topic 4 and Topic 5 reports for details).

As shown in Table 5.1, of these measures, the two with the greatest estimated potential to reduce nitrogen losses from agriculture to streams and rivers are:

- *Improved nitrogen management techniques.* This is estimated to offer the greatest potential reduction of nitrogen loading. Reducing "insurance" rates of nitrogen fertilizer,[4] improving management practices for storage and land application of manure,[5] improving management of runoff from feedlots, applying appropriate credits for previous crops and manure,[5] and using improved soil nitrogen testing methods could reduce nitrogen losses at the edge of fields by about 0.9–1.4 million metric tons per year.[6]

- *Alternative cropping systems.* If 10 percent of the corn–soybean farms in the Basin were changed to include alfalfa or alfalfa-grass mixes as crops, edge-of-field nitrogen losses could be decreased by an estimated 0.5 million metric tons per year.

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[4] *Data on "insurance" application of fertilizer (application at rates above agronomic recommendations) are sparse. "Insurance" application is an economic wager: the producer is gambling that all other factors influencing crop production will be optimal in a given year and that an extra 10–20 pounds of nitrogen fertilizer per acre would result in increased yields. In reality, this is a poor wager. Plant nitrogen is obtained from both soil reserves and applied nitrogen: thus, response is not solely a function of "this year's application," but is a function of the total available nitrogen status. Agronomic recommendations are developed taking these factors into account. Therefore, insurance applications are in most cases wasted, and the extra nitrogen is lost from the field and may lead to increased loadings to the aquatic environment.*

[5] *In practice, according to the Potash and Phosphate Institute, nitrogen use on corn in Iowa in 1996 was within the range of agronomic recommendations, when manure was not used but exceeded agronomic recommendations by more than 30 percent, or about 33 kg of nitrogen/ha (30 lb/acre) when manure was used.*

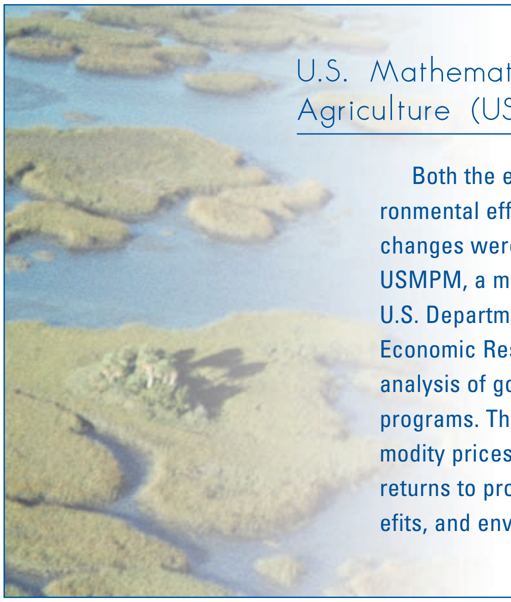
[6] *Note that these estimates of the impacts of changes in agricultural practices are for reductions at the edge of the field; estimated edge-of-field source reductions do not translate to equivalent reductions in nitrogen loadings to the Gulf, because only a portion of nitrogen sources in the Basin reaches the Gulf.*

Estimates of impact are based on field tests and case studies described in the Topic 5 report.

Measures to reduce nutrient loads would generally have net costs. Assuming constant levels of efficiency, large decreases in nutrient use below agronomic rates would lead to reduced agricultural productivity in the MARB and reduced total production as marginally fertile land is retired. The agriculture sector's response to these alternative management strategies was simulated with the U.S. Mathematical Programming Model for Agriculture (USMPM), described below. The model predicts both the economic effects and the changes in nitrogen loading under the various scenarios examined.

The USMPM modeling analysis provided a range of potential results that focusing a variety of nitrogen-reduction strategies in the Mississippi Basin could achieve. The analyses showed that as a result of different approaches to nitrogen reduction, shifts in production could be expected both inside and outside the Basin. Many producers inside the Basin would find that reducing crop acreage would benefit them, whereas many producers outside the Basin would find advantage in expanding their cropped acreage. For example, reducing edge-of-field nitrogen loss by 20 percent (in the most cost-effective manner) could result in a 5.8 percent decline in crop acreage in the Basin with a potential 2.8 percent increase in cropland outside the Basin. This same scenario could also be expected to increase edge-of-field nitrogen losses outside the Basin by about 8 percent due to an increase in production. Modeling analyses indicated that the higher the level of nitrogen loss reductions from agriculture shown in the Basin, the more pronounced shifts in regional production could be expected, and these production shifts could increase nutrient-related problems for other regions. Clearly, the degree and pattern of production shifts that could be realized in response to each alternative strategy would depend on the nature of the strategy selected (the mix of practices used), the size of the region affected, and its location (environmental conditions).

The USMPM modeling analysis predicts that edge-of-field nitrogen losses can be reduced by 20 percent (941,000 metric tons/yr) using various management practices at a total societal cost under economically optimum conditions of $831 million/yr, or $0.88 per kg reduction in edge-of-field nitrogen flux. This result assumes all factors of production are adjusted in the most efficient manner. Although meeting the 20 percent reduction in edge-of-field nitrogen loss could also be achieved by targeting fertilizer reductions only, it would require a 45 percent reduction in fertilizer use, resulting in costs of $2.85 per kilogram of nitrogen reduction. However, smaller reductions would be more attractive on a per kilogram basis: a 20 percent reduction in fertilizer would reduce edge-of-field losses by 503,000 metric tons/yr (about 10 percent) at a total societal cost of $347 million, or $0.69 per kilogram. As part of the economic analysis, the impact of raising the price of fertilizer by increasing fertilizer taxes (an approach designed to spur farmers to find ways to reduce fertilizer use) was evaluated. However, the analysis showed that to achieve a 20 percent reduction in edge-of field losses, such taxes would have to reach 500 percent of current retail price for fertilizer. The resulting cost to individual farmers and society as a whole was predicted to be much greater than other approaches evaluated (see Table 5.3 on page 45).



U.S. Mathematical Programming Model for Agriculture (USMPM)

Both the economic and the environmental effects of agricultural changes were estimated using the USMPM, a model developed by the U.S. Department of Agriculture's Economic Research Service for analysis of government commodity programs. The model calculates commodity prices and quantities, net returns to producers, net social benefits, and environmental emissions recognizing spatial variation and explicitly representing various management practices used by farmers. Adjustments to crop production can be estimated in response to restrictions placed on nitrogen or land use by altering any or all of the following: acreage planted, crop mix, rotations used, tillage practices, and fertilizer application rates (see the Topic 6 report, p. 25ff., for details).

Table 5.1 Potential Approaches to Reducing Nitrogen Inputs

Approach	**Potential Nitrogen Reduction** *(Thousands of metric tons/yr)*
Changing Farm Practices	
Nitrogen management *(Reduction in "insurance" rates of N fertilizer application, improved management practices for storage and land application of manure, improved management of runoff from feedlots, and crediting of nonfertilizer nitrogen)*	900–1,400[a]
Alternative cropping systems *(Perennial crops in lieu of corn and soybeans on 10% of acreage)*	500[a]
Reduction in Point Sources	
Tertiary treatment of domestic wastewater	20

[a] Note that these estimates of the impacts of changes in agricultural practices are for reductions at the edge of the field; estimated edge-of-field source reductions do not translate to equivalent in nitrogen loadings to the Gulf, because only a portion of nitrogen sources in the Basin reaches the Gulf.

Point sources of nitrogen, as well as urban nonpoint sources, also contribute to the total nitrogen load to the Gulf. Nitrate concentrations in urban nonpoint sources are generally not high, compared to urban point sources or Corn Belt cropland. Urban areas constitute only 0.6 percent of the Basin; thus, the contribution of urban nonpoint sources is comparatively small but has not been precisely estimated. Point sources constitute less than 2 percent of nitrogen inputs to the Basin, or about 11 percent of the nitrogen inputs to the Gulf. Higher unit costs for reductions in nitrogen from domestic wastewater partly reflect the fact that these sources are currently regulated and have realized pollution control costs already. Biological nitrogen removal from urban point sources typically costs $40 per kilogram of nitrogen removed. However, in some cases, cost-effective reductions in nitrogen load could be realized.

Atmospheric deposition of nitrogen (wet and dry nitrate, wet ammonia, and organic nitrogen) is estimated to be about 10 percent of the nitrogen input to the Basin. The costs of reducing atmospheric deposition of nitrogen are estimated to be $20–100 per kilogram of nitrogen.

Nitrogen trading among all sectors could offer opportunities to reduce costs overall.

Restoring and Enhancing Denitrification and Nitrogen-Retention Processes

A second general approach to reducing nitrogen flux to the Gulf of Mexico is to place or restore ecosystems that are effective nitrogen sinks along the paths of nitrogen flow from sources to the Gulf. Table 5.2 summarizes the impacts of denitrification options.

Nitrogen transformations in wetlands and riparian soils, surface water, and ground water involve several microbiological processes, some of which denitrify—that is, make the nitrogen effectively unavailable for plant uptake. Wetlands also serve as traps for phosphorus, which limits primary production within the Basin and, under some conditions, on the shelf in the Gulf.

High rates of denitrification are possible, but wetlands and riparian zones can also act as sources of nitrogen under some conditions. Loading rates (flow times nitrogen concentration of inflowing water) dictate the effectiveness of wetlands in reducing nitrogen. The most effective use of wetland restoration and creation would be in watersheds that discharge high amounts of nitrogen. Retention time is also important. Storm events, if significant enough, can cause nitrogen to move rapidly through the system, bypassing effective retention.

Extensive experience with flow-through wetland systems suggests a narrow range centered around 10–25 g N/m^2/yr as a reasonable target for denitrification by wetlands. Assuming denitrification at 15 g N/m^2/yr (150 kg N/ha/yr), 2.1 million hectares (5 million acres, or 0.7 percent of the Mississippi River Basin area) of constructed or restored wetlands would reduce nitrogen load to the Gulf of Mexico by 20 percent. The current national goal is to restore wetlands at a rate of 100,000 acres/yr (about 40,000 ha/yr) (see the Clean

Vegetated buffer areas reduce both surface and subsurface flux of nitrogen to streams and rivers. Riparian buffers can be particularly effective in capturing nutrients (and providing other protection) during floods.

U.S. DEPARTMENT OF AGRICULTURE

Water Action Plan, available at <http://www.cleanwater.gov>). The total direct costs for permanent easements and restoration of wetlands to reduce nitrogen load by 20 percent was estimated to be $4.7 billion. Annual costs, including net effects on consumers and producers plus annualized wetland restoration costs, were estimated to be $3.1 billion, or about $8.90 per kilogram reduction in nitrogen flux per year. There would be ecological and wildlife benefits in addition to those that might accrue in the Gulf from using this approach.

Riparian areas are vegetated areas, generally forested or grassed, next to water resources. They have been shown to be effective in removing nitrates from ground water as it passes through the vegetated buffer. Typically, denitrification rates are 2-6 g N/m^2/yr. Assuming denitrification at 4 g N/m^2/yr (40 kg N/ha/yr), 7.8 million hectares (19 million acres, or 2.7 percent of the Basin) of additional riparian buffers would be needed to reduce nitrogen load to the Gulf by 20 percent.

A current national goal is to establish two million miles of conservation buffers on agricultural lands (also per the Clean Water Action Plan). Total direct costs for permanent easements and restoration of 27 million acres of riparian buffers were estimated to be $46.3 billion, equating to $18.0 billion annually in changes to consumer and producer surpluses plus annualized restoration costs, or about $26 per kilogram reduction in nitrogen flux per year.

Table 5.2 Potential Approaches to Increasing Denitrification

Approach	**Potential Nitrogen Reduction** *(Thousands of metric tons/yr)*
Creating and restoring 5–13 million acres of new wetlands	300–800
Creating and restoring 19–48 million acres of riparian bottomland hardwood forest buffers	300–800
Diverting rivers in coastal Louisiana	50–100

Separation of the Mississippi River from its floodplain and coastal estuaries may be an important factor in supplying nutrients to the Gulf. The river once spread out over the Delta during flood periods. Today, however, with the exception of such locations as the Bonne Carre Spillway and the Atchafalaya Basin, the river is mostly shunted directly to the sea. Through enhanced water management strategies, it may be possible to increase the amount of water reaching inland and coastal wetlands, and thereby increase nitrate removal from the water and reduce coastal land loss. Using a denitrification rate of 10 g N/m^2/yr based on studies at Caernarvon, Louisiana, and other locations, diverting 13 percent of the total river flow over 1.2 million acres (500,000 hectares) would remove 50,000 metric tons of nitrate per year. However, without upstream controls, the system might become nitrogen-saturated, or it might release nitrogen in a different form, in a different season, or in a different location. A recent study (Turner 1999) compared nutrient concentrations entering and leaving the Atchafalaya River basin, a major floodway used to divert floodwaters from the Mississippi and Red Rivers to the Gulf during the annual high-water season. This study found that nitrate concentrations remained essentially unchanged from upstream to downstream monitoring stations. However, enhanced water management strategies within the floodway could improve the potential to remove nitrate from waters flowing through this area. Other studies have shown that harmful algal blooms may result when large quantities of Mississippi River water are diverted into coastal areas.

The construction and restoration of wetlands and riparian zones in the Basin to reduce nutrients would contribute to several important national goals, including those for drinking-water protection, adding to the nation's disappearing wetland habitat, improving river ecosystems, enhancing terrestrial wildlife in river corridors, and mitigating the effects of floods. This restoration of wetlands is in keeping with recommendations by the National Research Council's Committee on the Restoration of Aquatic Ecosystems (NRC 1992), which called for a national program of wetland restoration that would contribute to an overall gain of 10 million acres by the year 2010. Well-placed wetlands and riparian buffers generally support larger populations of wildlife because of the diverse habitats they provide. The restoration of riparian vegetation improves the ecological condition of streams and rivers and protects the aquatic communities that depend on them. Roots of riparian vegetation stabilize the stream bank and prevent both bank erosion and downstream sedimentation. The National Research Council also called for restoration of about 640,000 kilometers (400,000 miles) of streams, rivers, and floodplains across the nation (NRC 1992).

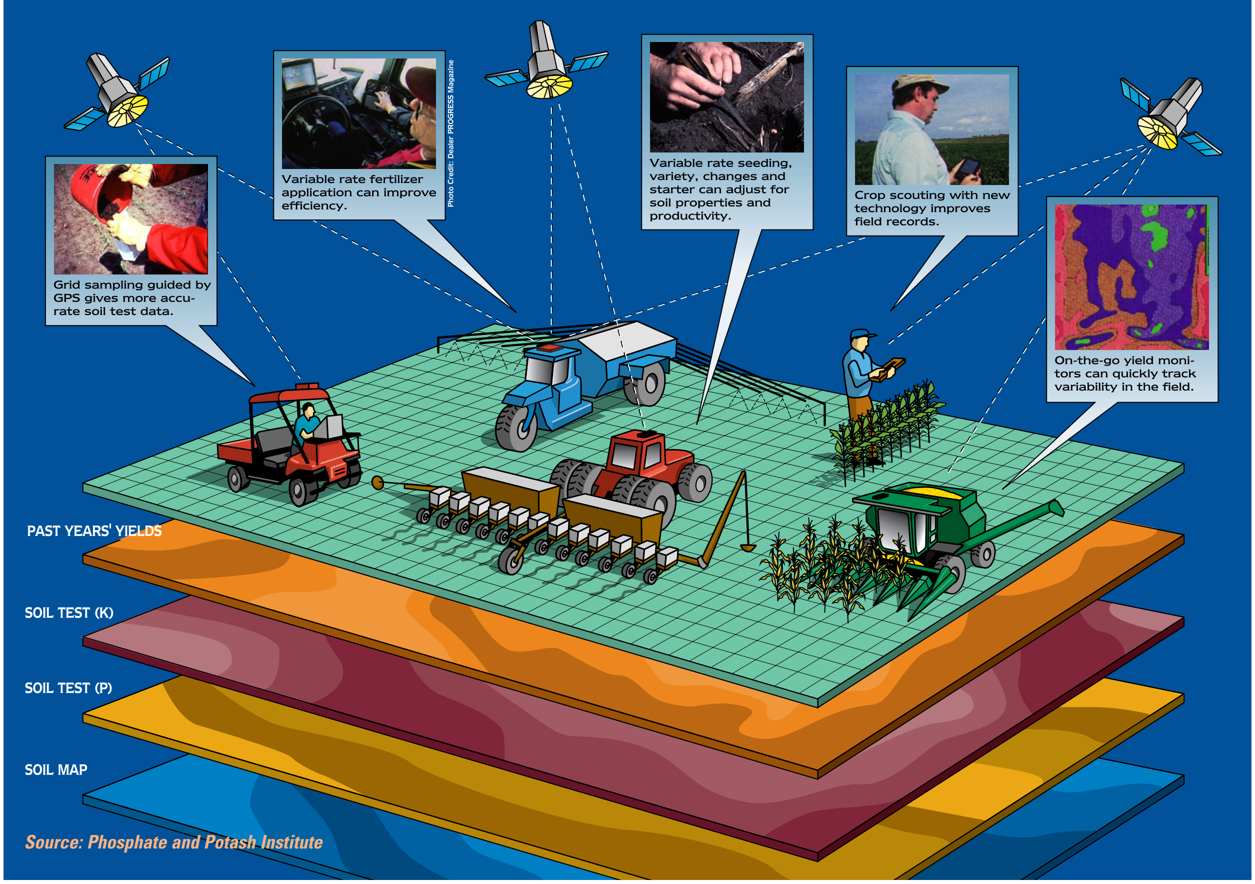
Cost-Effective Strategies

Various potential components of a program to reduce nitrogen loads to the Gulf via the MARB system were analyzed to evaluate their cost-effectiveness; their impacts on the economy, farmers, and consumers; and the reductions in loads (Table 5.3).

Direct costs, including changes in consumer and producer surpluses and easement and restoration costs for wetlands, were estimated using the USMPM. All of the nutrient-reduction approaches will also produce environmental benefits within the drainage basin. These include the values associated with restored wetlands, reduced soil erosion, reduced nitrogen contamination of drinking water, reduced vulnerability to floods, enhanced wildlife habitat and improved recreational water quality. Other potential benefits of nutrient-reduction activities include more efficient use of organic and inorganic fertilizers (see Figure 5.1) and the energy associated with them, lower overall fertilizer costs, decreased health risk from contamination of public and private drinking-water supplies, and improved aquatic habitat in streams, lakes, rivers, and estuaries. Good estimates for the economic value of these benefits are only available for a few categories, such as wetlands and erosion. When these estimated benefits are factored in, the net costs of wetlands and farm practices become close: 20 percent edge-of-field nitrogen-loss reduction was estimated to have a net cost of $0.80 per kilogram ($0.36 per pound), while 5 million acres of wetlands would have a net cost of $1.00 per kilogram ($0.45 per pound).

An optimal strategy would take appropriate advantage of the full range of possible approaches to deal with hypoxia in the Gulf. Implementation mechanisms, including incentive payments, voluntary stewardship and technical assistance programs, more stringent requirements for regulated facilities or various combinations of these approaches, have advantages and disadvantages in various circumstances and locales; however locale-specific considerations were beyond the scope of this assessment. Since, generally, the costs per pound of nitrogen kept out of the river system and Gulf, or removed by biogeochemical processes in restored wetlands or riparian areas, are in the same order of magnitude, these regional or site-specific circumstances may drive the choice of the preferred mix of actions to address hypoxia—no single approach is clearly far more economical or costly.

FIG. 5.1 High-Tech Tools for Site-Specific Crop Nutrient Management



Grid sampling guided by GPS gives more accurate soil test data.

Variable rate fertilizer application can improve efficiency.

Photo Credit: Dealer PROGRESS Magazine

Variable rate seeding, variety, changes and starter can adjust for soil properties and productivity.

Crop scouting with new technology improves field records.

On-the-go yield monitors can quickly track variability in the field.

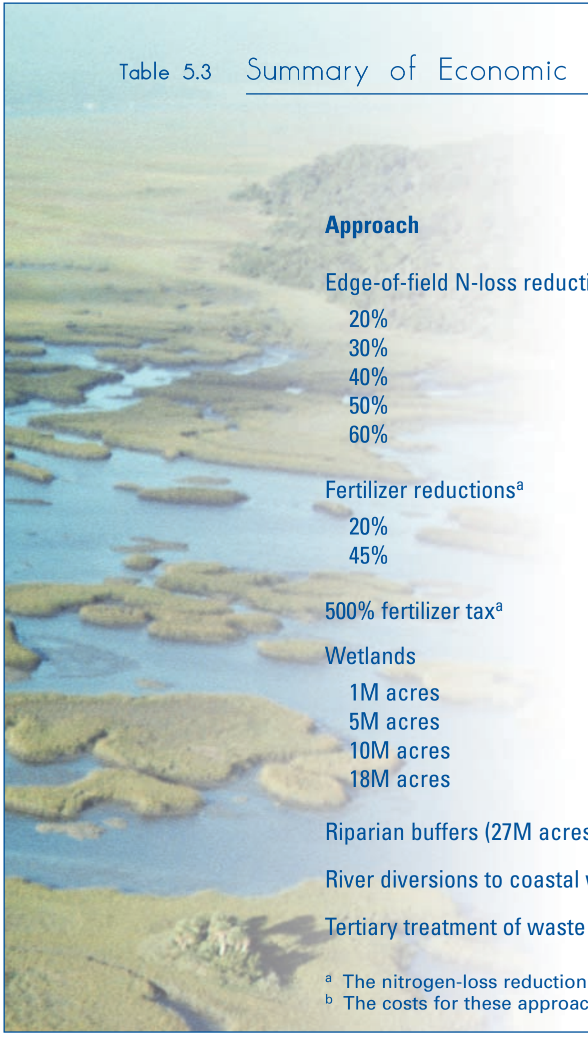
Source: Phosphate and Potash Institute

Nutrient application can be optimized based on geo-referenced records of soil test values, soil yield potential, and previous yield and application histories.

The benefits of a program to reduce nitrogen loads to the Gulf are difficult to quantify. Although there are known impacts to the Gulf ecosystem, an economic analysis based on past data did not detect a direct relationship between hypoxia and Gulf fisheries. The information to estimate the benefit value for such actions as restoring the ecological communities in the Gulf or improving water quality in the Basin is not available.

Another factor important in assessing the impact of potential actions on restoring damaged resources and on mitigating and controlling hypoxia in the Gulf is the uncertainty around and contribution of time lags. It appears that a substantial quantity of nutrient storage in soils and ground water has built up over many decades. This suggests that continuing loads may contribute to elevated discharges to the Gulf perhaps for decades, even after reduction programs are implemented.

Table 5.3 Summary of Economic Costs of N-Loss Reduction Actions

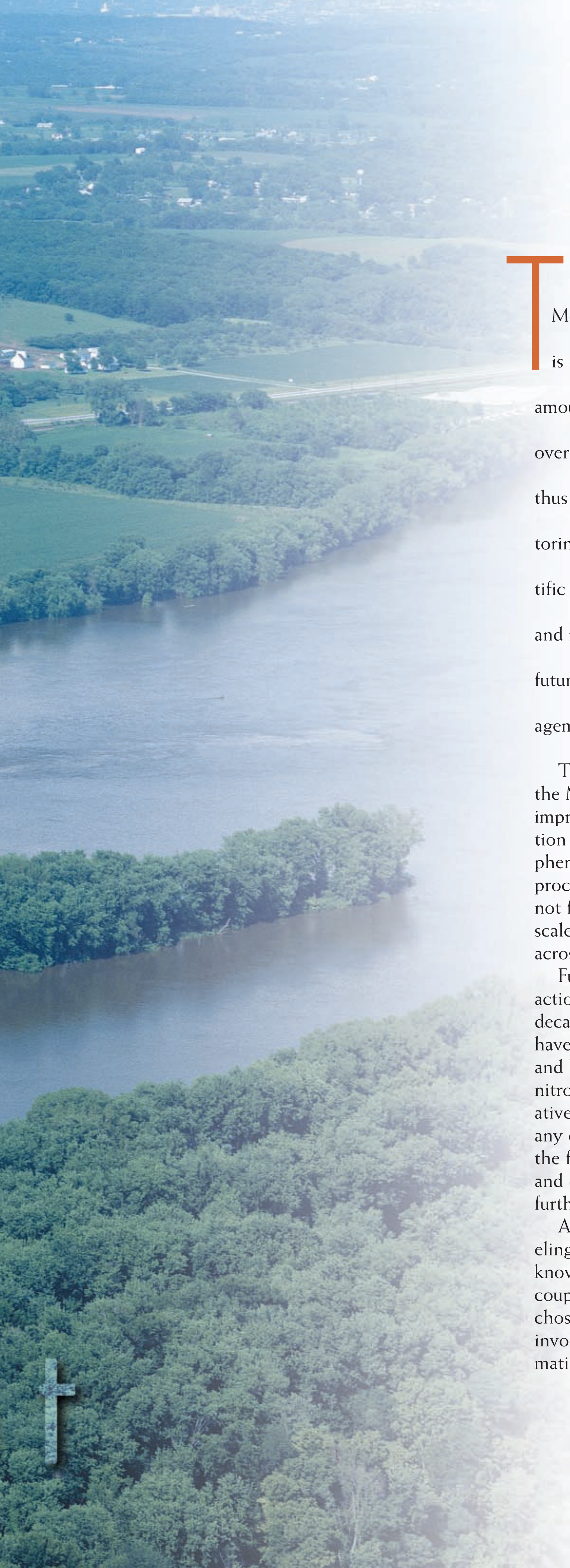


Approach	**N-Loss Reduction** *(Thousands of metric tons/yr)*	**Net Cost within Agricultural Sector** *($/kg N loss)*	**Net Cost, incl. Environmental Benefits** *($/kg N loss)*
Edge-of-field N-loss reductions, through economically optimum actions[a]			
20%	941	0.88	0.80
30%	1,412	1.90	1.80
40%	1,882	3.37	3.25
50%	2,352	5.20	5.08
60%	2,822	7.48	7.37
Fertilizer reductions[a]			
20%	503	0.69	0.67
45%	1,027	2.85	2.81
500% fertilizer tax[a]	1,027	14.54	14.50
Wetlands			
1M acres	67	6.06	- 2.19
5M acres	350	8.90	1.00
10M acres	713	10.57	2.81
18M acres	1,300	11.93	4.27
Riparian buffers (27M acres)	692	26.03	
River diversions to coastal wetlands[b]	75	~6	
Tertiary treatment of waste water[b]	20	~40	

[a] The nitrogen-loss reduction effects of these approaches are estimated at the edge of the field.
[b] The costs for these approaches include engineering and construction costs only.

Adaptive Managemen

Action, Monitoring, and Research

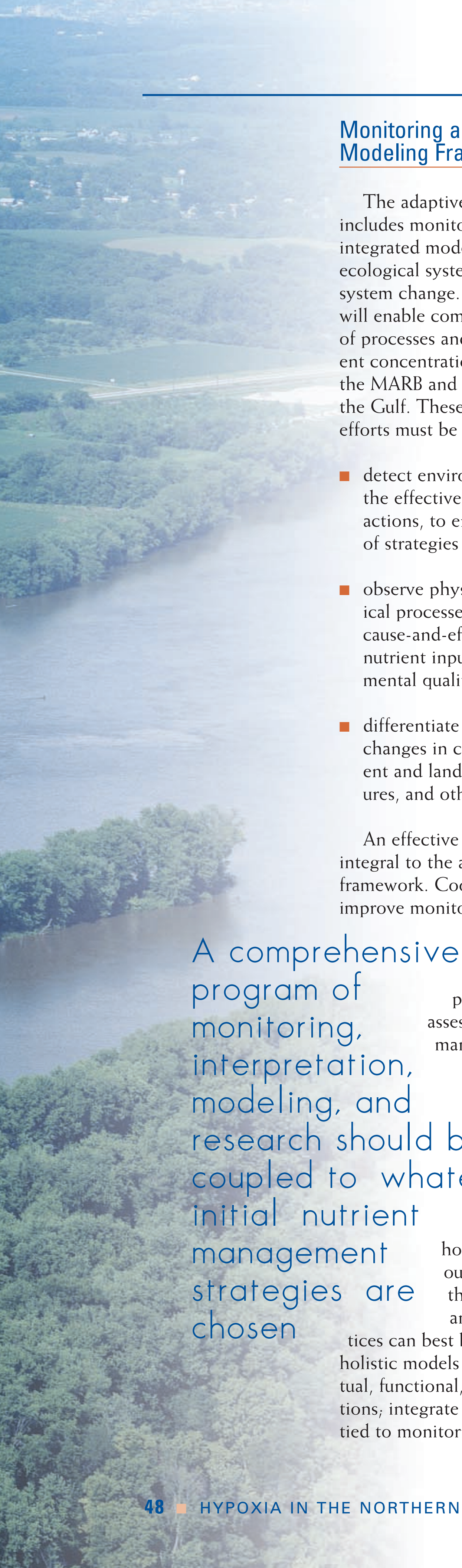


This assessment of the causes and consequences of Gulf of Mexico hypoxia, and its analysis of options for dealing with it, is drawn from the assembly and peer review of a massive amount of direct and indirect evidence collected and reported over many years of scientific inquiry. The findings presented are thus well founded and are grounded in those research and monitoring results. There are, however, always uncertainties in scientific analysis. This section identifies areas of further monitoring and research that are needed to reduce those uncertainties in future assessments and to aid decision making in an adaptive management framework.

The complex nature of nutrient cycling and transport within the MARB and Gulf of Mexico make it difficult to predict specific improvements in water quality that will occur for a given reduction in nutrient inputs. Nutrient cycling is affected by atmospheric, watershed, riverine, and marine processes. Many of these processes, such as nitrogen transformations in river reaches, are not fully understood at the local scale at which they occur. Large-scale, multidisciplinary interpretations that integrate knowledge across these hydrologic compartments are difficult.

Further, it is clear that environmental responses to management actions in the MARB likely will be slow, possibly requiring decades of data to demonstrate statistically that remedial actions have helped the recovery of oxygen concentrations in the Gulf and have improved water quality in the Basin. For example, the nitrogen balance in the soil zone and ground water will adjust relatively slowly to changes in nitrogen inputs and outputs, slowing any change in the flux of nitrogen to the Gulf. At the same time, the flux of nutrients to the Gulf most likely will respond quickly and dramatically to large variations in precipitation and runoff—further complicating measurement of reductions in nutrient flux.

A comprehensive program of monitoring, interpretation, modeling, and research to facilitate continual improvement in scientific knowledge and adjustments in management practices should be coupled to whatever initial nutrient management strategies are chosen (see Figure 6.1). This adaptive management scheme involves continual feedback between interpretation of new information and improved management actions.



Monitoring and Research in a Modeling Framework

The adaptive management framework includes monitoring programs that use integrated models of the hydrologic and ecological systems for interpretation of system change. Whole-system monitoring will enable comprehensive interpretation of processes and linkages that affect nutrient concentrations and transport within the MARB and development of hypoxia in the Gulf. These coordinated monitoring efforts must be able to:

- detect environmental trends to evaluate the effectiveness of management actions, to enable effective adaptation of strategies over time;
- observe physical, chemical, and biological processes and their roles in the cause-and-effect relationships between nutrient inputs and resulting environmental quality; and
- differentiate among trends caused by changes in climate, streamflow, nutrient and landscape management measures, and other concurrent factors.

An effective research strategy is also integral to the adaptive management framework. Coordinated research efforts improve monitoring designs, support the interpretation of monitoring output, and increase the predictive power of models and other assessment tools used in the management process.

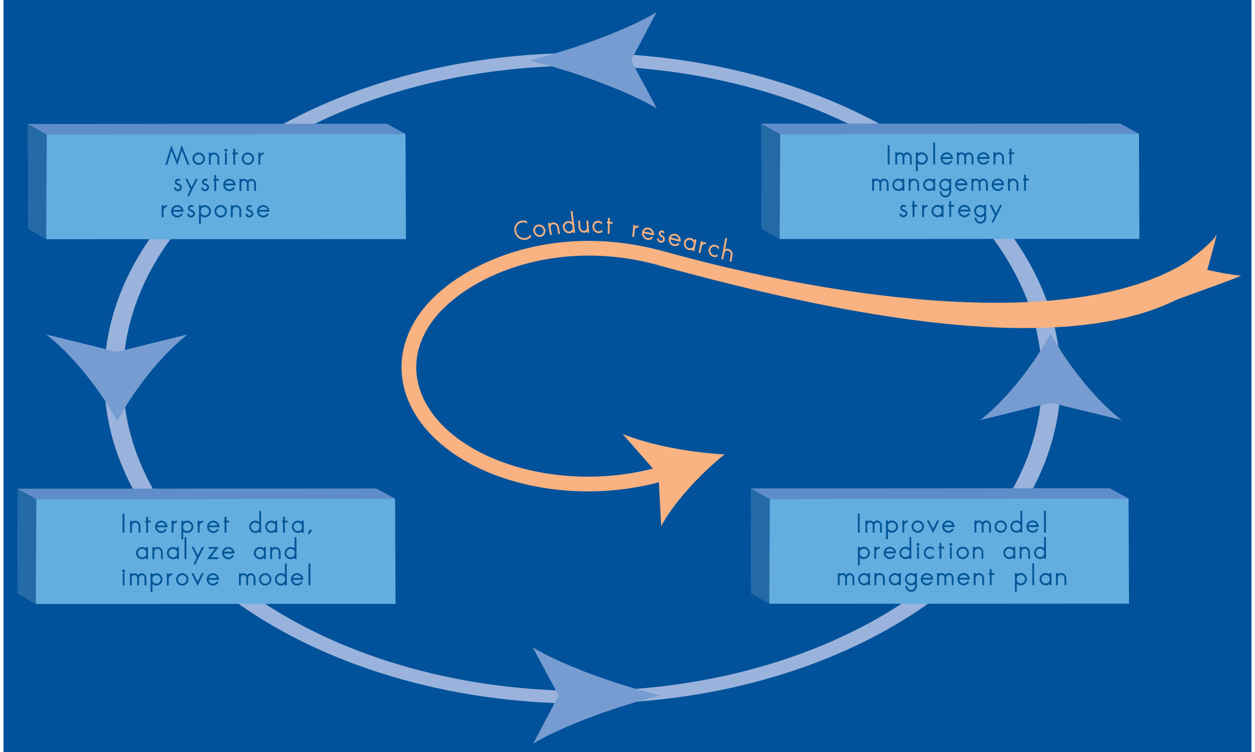
> A comprehensive program of monitoring, interpretation, modeling, and research should be coupled to whatever initial nutrient management strategies are chosen

For a system as large and complex as the MARB and the northern Gulf of Mexico, monitoring and research should be integrated using holistic models that simulate our understanding of how the overall system functions and how management practices can best be implemented. Such holistic models include a suite of conceptual, functional, and numerical formulations; integrate research findings; and are tied to monitoring programs designed to both provide input variables and verify model outputs. River monitoring data should be integrated with offshore ecological and oceanographic data on appropriate time scales. An effective modeling framework would include models that simulate:

- transport and transformation of nutrients (nitrogen, phosphorus, and silica) from natural, urban, and agricultural landscapes to ground water and surface waters;
- inputs and outputs of nutrient flow throughout the landscape to improve estimates of nutrient mass balances;
- biogeochemical cycling and water quality effects of those nutrients on river ecosystems within the drainage basin;
- oceanographic and climate influences on those nutrients and their impacts on Gulf productivity as they leave the Mississippi–Atchafalaya River system;
- impacts of increased nutrient flux on productivity in the northern Gulf of Mexico ecosystem, including commercially and recreationally important fisheries; and
- three-dimensional coupling of biological and physical processes in the Gulf ecosystem influenced by the Mississippi River discharge.

Within this larger modeling framework, important research and monitoring needs have emerged from this assessment. Monitoring gaps are found in environmental programs of the MARB and Gulf, as well as in programs that monitor management measures. Research needs include improving the quantitative understanding of the biogeochemical cycling of nutrients within the watershed and the Gulf and its relationship to the dynamics of organic carbon flux in the Gulf; the roles of long-term change in climate, hydrology, and population in year-to-year and long-term trends in nutrient loads and hypoxia; and the social and economic impacts of various management and policy alternative strategies.

FIG. 6.1 Adaptive Management Framework



Source: Herb Buxton, U.S. Geological Survey

The adaptive management concept connects monitoring, analysis, and management actions with continuous feedback for improvement. New understandings from research should be interwoven throughout the process.

Monitoring Needs

A comprehensive monitoring program requires both measurement of environmental response in the MARB and the Gulf of Mexico and tracking indicators of programmatic progress toward mitigating excessive nutrients.

Environmental Responses in the Gulf

Essential components of an environmental monitoring program in the Gulf of Mexico include efforts to:

- Document the temporal and spatial extent of shelf hypoxia, and to collect basic hydrographic, chemical, and biological data related to the development and maintenance of hypoxia over seasonal cycles. A triad of mid-summer shelf-wide hypoxia surveys, monthly transects off Terrebone Bay, and instrumented arrays at stations in the core of the hypoxic zone would provide an optimal combination of spatial and temporal scales of measurement and would be consistent with the existing long-term data. Establishing multiple vertical and horizontal instrument arrays oriented cross-shelf and along-shelf will better define processes that control the temporal and spatial development of hypoxia.

- Improve the collection of ecological, production, and economic information related to fishery and nonfishery species.

- Facilitate synthesis and interpretation of these data through an integrated database.

Environmental Responses in the MARB

Essential components of an environmental monitoring program in the MARB include efforts to:

- Document the flux of nutrients, carbon, and selected other water quality constituents from the MARB to the Gulf of Mexico systematically on at least a monthly basis and more frequently at high flows—at least 25–30 times annually. Additional monitoring sites in the main channel of the Mississippi River are needed to evaluate the extent of nutrient retention/loss within the lock-and-dam system, and to clarify the extent of nutrient retention in the lower Mississippi. There is a need to re-establish monitoring of nutrients, carbon, and selected other water quality constituents in the major subbasins (the 42 interior basins) throughout the MARB and to establish monitoring in selected small basins within some of the 42 interior basins where the effects of changes in land management practices on nutrient concentrations and yields will be easiest to detect and quantify.

- Monitor nutrients from atmospheric wet deposition in the MARB, and expand the current limited monitoring of nutrients in atmospheric dry deposition. This information is needed to determine if nutrient management strategies affect precipitation chemistry.
- Establish a periodic inventory of effluent reporting conducted through the National Pollution Discharge Elimination System (NPDES) to systematically improve current estimates of nitrogen and phosphorus loads discharged to streams from municipal and industrial point sources.
- Improve measurements for soil nitrogen and nitrogen loss.

Programmatic Measures

Ongoing programs are taking action to improve water quality conditions within the MARB and Gulf of Mexico. Coordination of current and future programs to improve water and ecological conditions can increase their overall effectiveness in achieving goals. Some major measures of progress of ongoing programs include inventories of:

- changing patterns in other nutrient inputs to the Basin, such as fertilizer use and manure application and disposal;
- acres of land leased annually through the Conservation Reserve Program and the Conservation Reserve Enhancement Program;
- acres of created or restored wetlands implemented through the Wetlands Reserve Program, the Emergency Wetlands Reserve Program, the Clean Water Act section 319 program, and the various environmental restoration and related authorities, such as the Coastal Wetlands Planning, Protection and Restoration Act, the Environmental Management Program and other Corps of Engineers programs, and the Partners for Wildlife Program;
- acres of riparian buffers implemented through the Conservation Buffer Initiative and the Clean Water Act section 319 program; and
- actions to reduce nutrient runoff stimulated by the Environmental Quality Incentive Program and the Clean Water Act section 319 program.

Research Needs

The research needs outlined below fall into two categories: (1) immediate priorities that are essential for designing near-term management actions, and (2) longer-term priorities that fill critical gaps in understanding as well as guide efforts to mitigate and control the effects of hypoxia and excess nutrients.

Immediate Research Priorities

Ecological Effects of Hypoxia. A better definition of the past, current, and potential impacts of hypoxia on both commercially and ecologically important species and ecosystems is needed. New retrospective analyses over longer temporal and spatial scales, based on data from marine sediment cores should improve the historical perspective. Better understanding of other factors that affect the ecological health and fisheries of the northern Gulf of Mexico is needed to uniquely identify the role of hypoxia and to design effective management actions.

Contemporary effects. Additional data sources have yet to be examined exhaustively, most notably the SEAMAP database, which includes long-term fishery-independent data on nektonic species' composition in the northern Gulf of Mexico ecosystem. Model analyses of trophic structure and ecosystem dynamics—which will help identify affected fishery resources, and assess potential future impacts—are also needed.

Historical perspective. The northern Gulf of Mexico ecosystem may have already undergone significant ecological change prior to initiation of the first in-depth scientific investigation in the mid-1980s. Thus, the system is likely in a transitional state as nutrient loading approaches new plateaus. Further research and assessment of these longer-term trends are needed. New retrospective analysis over longer temporal and spatial scales, based on data from marine sediment cores should improve the historical perspective.

Watershed Nutrient Dynamics. There is a need to better understand the dynamics and timing of movement of nitrogen and other nutrients from the edge of the field in agricultural landscapes to small streams and tributaries. Additional information is also needed on the geographic distribution and design criteria for targeting wetland creation and restoration efforts and to determine if other strategies (e.g., riparian buffers) and mixtures provide the best nitrate reduction for the least cost.

Research Priorities

Immediate Research Priorities

Ecological Effects of Hypoxia

- *Contemporary effects*
- *Historical perspective*

Watershed Nutrient Dynamics

- *From "edge-of-field" to streams*
- *Wetlands creation*

Agricultural Practices

- *Watershed/farm-scale studies*
- *Experimental policies and practices*

Longer-Term Research Priorities

Nutrient Cycling and Carbon Dynamics

- *Soil organic nitrogen*
- *In-stream, in-river, and Gulf sediment denitrification*
- *Nutrient cycling in the northern Gulf of Mexico*
- *Atmospheric deposition*

Long-Term Changes in Hydrology, Climate, and Population

- *Large-scale climate effects*
- *Flood events*
- *Mississippi–Atchafalaya River delta management and restoration*
- *Point-source and urban nonpoint-source controls*

Economic and Social Impacts

- *Economic values of river and lake water quality improvements*
- *Economic values of Gulf water quality improvements*
- *Economic trade-offs in agricultural systems*

From edge of the field to streams. There is a need to better understand the dynamics and timing of movement of nitrogen and other nutrients from the edge of the field in agricultural landscapes to small streams and tributaries. This is especially true as it relates to tile drains and other practices that move nitrogen and other plant nutrients through the soil drainage system.

Wetlands creation. Additional information is needed on the geographic distribution and design criteria for targeting wetland creation and restoration efforts. There is also a need to determine which other strategies (e.g., riparian buffers) and mixtures provide the best nitrate reduction for the least cost. It is important to understand and quantify the potential for changes in the production of the greenhouse gas N_2O that could occur from wetland creation and restoration efforts.

Agricultural Practices. While improvements in agricultural practices have been achieved in recent years and the efficiency of nitrogen use has increased substantially, there is a need to better quantify the effects of on-farm practices and methods that intercept agricultural nutrients between the field and ground water and adjacent streams.

Watershed/farm-scale studies. There is a critical need to scale up from experimental plots to watershed/farm-scale studies falling into two classes. The first class includes studies to better quantify and demonstrate the effects of on-farm practices, such as precision farming, altered lateral spacing of drainage tiles, controlled water table levels, use of fall and winter cover crops, altered timing of fertilizer application, and exploring alternatives to traditional crop rotations. The second class includes studies on better means to intercept agricultural nutrients between the field and ground water and adjacent streams through riparian buffers, wetlands, and other means.

Experimental policies and practices. Measuring and quantifying the effectiveness of recent policies and voluntary actions to reduce nutrient inputs should be coordinated on a basin scale. There is a need to better quantify and understand the impacts of current and proposed policies (e.g., nutrient trading, fertilizer-use insurance) that increase incentives to reduce nitrogen loss. Additionally, there is a need to evaluate how future policies or practices might best be implemented and administered under various institutional frameworks.

Longer-Term Research Priorities

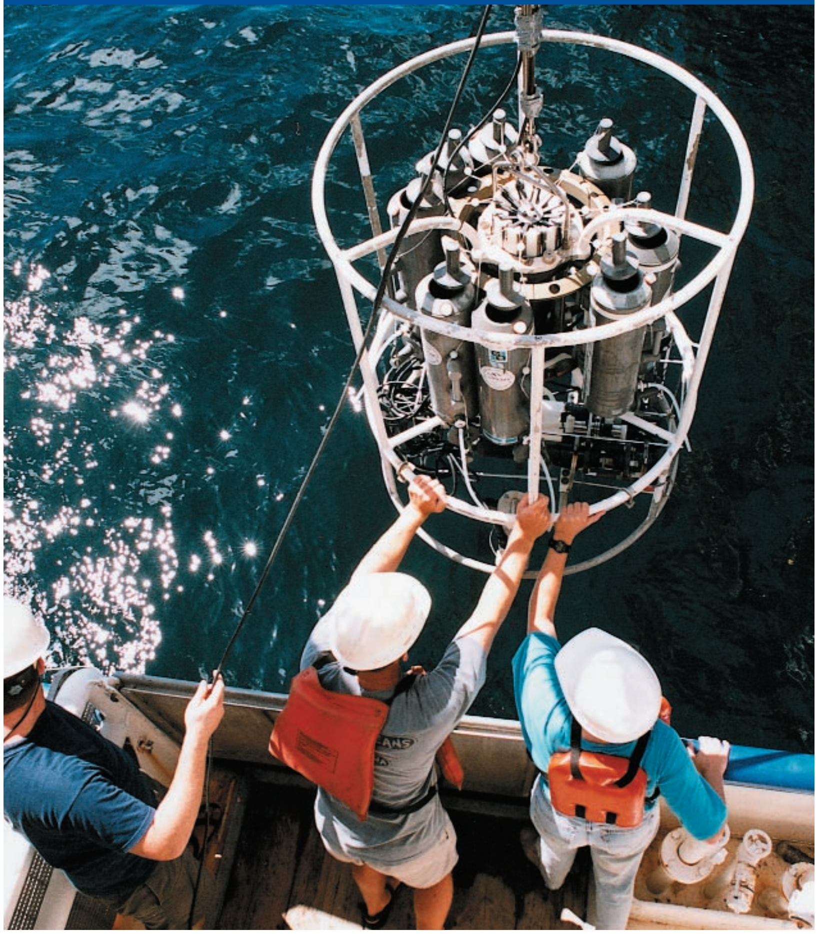
Nutrient Cycling and Carbon Dynamics. Research is needed to improve understanding of nutrient cycling and carbon dynamics, particularly variations across the Basin and the relationship of site-specific actions to Basin-scale effects.

Soil organic nitrogen. Scientific investigations indicate that the soil zone is a huge storage reservoir of nitrogen. Both inputs to and outputs from this reservoir have increased dramatically in recent decades. Research is needed to better understand mineralization and immobilization processes, to develop better means to measure the amount and forms of nitrogen in the soil reservoir, and to develop strategies to minimize leaching of nitrate from the soils to the streams.

In-stream, in-river, and Gulf sediment denitrification. There is a need to better quantify denitrification and nutrient retention rates in small and large streams and in Gulf sediments, and to compare these rates to those achieved in riparian buffers and wetlands.

Nutrient cycling in the northern Gulf of Mexico. Further refinements of the relationships among nutrient fluxes, nutrient ratios, and nutrient cycling on the continental shelf in the Gulf are necessary. Such refinements would improve simulations of subsequent effects on primary productivity, species composition, development of hypoxia, and higher trophic-level productivity in the Gulf ecosystem.

Scientists deploy conductivity, temperature, and depth (CTD) instruments, along with dissolved oxygen sensors, to sample water conditions in the Gulf.



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Atmospheric deposition. Additional research on atmospheric deposition of nitrogen in the Gulf is needed to improve understanding of various cycling mechanisms involving different forms of nitrogen.

Long-Term Changes in Hydrology, Climate, and Population. Additional research is needed to more clearly identify, understand, and predict the effects of long-term changes in hydrology, climate, and population.

Large-scale climate effects. The relationship between large-scale climate patterns (e.g., long-term trends and changes in variability of precipitation) and their potential impacts on river flows, nutrient flux, and flow dynamics on the continental shelf need further evaluation. Changes in precipitation, temperature, and flow patterns may have significant long-term influence on the rate and pattern of nitrate flux within the basin, and on the physical constraints of nitrate assimilation in the northern Gulf. The potential effects of future global climate change on such large-scale climate patterns should also be taken into consideration.

Flood events. Episodic events, such as the Great Mississippi River Flood of 1993 not only have caused significant damage to life and property, but also have transported abnormally high quantities of nitrogen and phosphorus to the Gulf. Studies are needed to evaluate the potential role of flood prevention and control methods that seek to distribute and retain more floodwater within the Basin and thus increase nitrogen retention, while protecting against flood damage.

Mississippi–Atchafalaya River delta management and restoration. Studies are needed to improve understanding of nutrient cycling in the deltaic plain in order to guide possible changes in management activities, such as the diversion of floodwaters to delta backwaters and coastal wetland restoration.

Point-source and urban nonpoint-source controls. The cost of nitrogen reduction from point sources and from urban nonpoint sources has been analyzed on the basis of existing technologies and human population densities. The potential for additional population and landscape changes to offset reductions achieved in nitrogen loading from the Basin should be carefully evaluated.

Economic and Social Impacts. In the spirit of a "win-win" approach to action plan design and implementation, all potential ancillary social and economic benefits of management actions as well as potential adverse effects should be identified and considered in the design of monitoring and research activities.

Economic values of river and lake water-quality improvements. The benefits of reducing nutrient loads in the freshwater system are considered significant. A great deal of research into these benefits has been conducted. Most studies, however, have been site-specific and have been performed for selected watersheds or water uses. There is a growing need for an aggregated analysis of both direct (e.g., drinking-water protection) and indirect (increased recreation) improvements in water quality, for the Basin as a whole.

Economic values of Gulf water quality improvements. To date only the potential direct economic effects of Gulf hypoxia on commercial fish catch have been attempted. Additional work needs to be done to explore a broader range of ecological impacts, including potential impacts to biodiversity and to nonmarket-valued ecosystem goods and services.

Economic trade-offs in agricultural systems. Better estimates of cost savings to agricultural producers from reduced fertilizer nutrient inputs are needed. Similarly, better estimates of the social costs that could result from nitrogen management or reduction strategies (e.g., from dislocation in land use, agribusiness infrastructure, and farm communities) are needed.

Appendix

Glossary

algae: a group of chiefly aquatic plants (e.g., seaweed, pond scum, stonewort, phytoplankton) that contain chlorophyll and may passively drift, weakly swim, grow on a substrate, or establish root-like anchors (steadfasts) in a water body.

anoxia: the absence of dissolved oxygen.

benthic organisms: organisms living in association with the bottom of aquatic environments (e.g., polychaetes, clams, snails).

chlorophyll: pigment found in plant cells that are active in harnessing energy during photosynthesis.

copepod: zooplankton whose bodies are covered with a hard shell or crust; order of crustacea.

cyanobacteria: formerly known as blue-green algae.

demersal organisms: organisms that are, at times, associated with the bottom of aquatic environments, but capable of moving away from it (e.g., blue crabs, shrimp, red drum).

denitrification: nitrogen transformations in water and soil that make nitrogen effectively unavailable for plant uptake, usually returning it to the atmosphere as nitrogen gas.

diatom: a major phytoplankton group characterized by cells enclosed in silicon frustules, or shells.

edge-of-field nitrogen loss: a term that refers to the nitrogen that is lost or exported from fields in agricultural production.

eutrophic: waters, soils, or habitats that are high in nutrients; in aquatic systems, associated with wide swings in dissolved oxygen concentrations and frequent algal blooms.

eutrophication: an increase in the rate of supply of organic matter to an ecosystem.

hydrogen sulfide: a chemical, toxic to oxygen-dependent organisms, that diffuses into the water as the oxygen levels above the seabed sediments become zero.

hypoxia: very low dissolved oxygen concentrations, generally less than 2 milligrams per liter.

mesotrophic: intermediate between oligotrophic (low-nutrient) and eutrophic (high-nutrient) systems.

nitrate: inorganic form of nitrogen; chemically NO_3.

nonpoint: a diffuse source of chemical and/or nutrient inputs not attributable to any single discharge (e.g., agricultural runoff, urban runoff, atmospheric deposition).

nutrients: inorganic chemicals (particularly nitrogen, phosphorus, and silicon) required for the growth of plants, including crops and phytoplankton.

oligotrophic: waters or soils that have low concentrations of nutrients and have low primary productivity.

pelagic: living or growing in the water column or at the surface of the ocean near shore.

phytoplankton: plant life (e.g., algae), usually containing chlorophyll, that passively drifts in a water body.

plankton: organisms living suspended in the water column, incapable of moving against currents.

productivity: the conversion of light energy and carbon dioxide into living organic material.

pycnocline: the region of the water column characterized by the strongest vertical gradient in density, attributable to temperature, salinity, or both.

recruitment: the influx, initial survival, and establishment of new members into a population by reproduction or immigration.

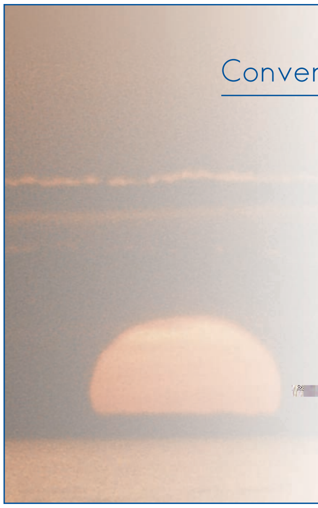
respiration: the consumption of oxygen during energy utilization by cells and organisms.

riparian areas: area adjacent to a river or other body of water.

senescence: the aging process in mature individuals; in plants, the process that occurs before the shedding of leaves.

stratification: a multilayered water column, delineated by pycnoclines.

zooplankton: animal life that drifts or weakly swims in a water body, often feeding on phytoplankton.



Conversion Table

Multiply	By	To Obtain
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km2)	0.3861	square mile
square kilometer (km2)	100	hectare
hectare (ha)	2.471	acre
kilogram (kg)	2.205	pound
metric ton (t)	1,000	kilogram
cubic meters (m3) per second	35.31	cubic feet per second
kilogram per sq. kilometer (kg/km2)	0.008924	pounds per acre

References

Bierman, Victor J., et al. 1994. A Preliminary mass balance model of primary productivity and dissolved oxygen in the Mississippi River plume/inner Gulf shelf region. *Estuaries* 17(4):886–99.

Bricker, S.B., et al. 1999. *National eutrophication assessment: Effects of nutrient enrichment in the nation's estuaries.* Silver Spring, MD: NOAA National Ocean Service. 71 pp.

Bureau of the Census. 1999. *Statistical Abstract of the United States 1998.* Washington, DC: U.S. Government Printing Office.

Caddy, J.F. 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Reviews in Fisheries Science* 1(1):57-95.

Carey, Anne E., et al. 1999. *The Role of the Mississippi River in Gulf of Mexico hypoxia,* Report No. 70, Tuscaloosa, AL: Environmental Institute, University of Alabama. 79 pp.

Diaz, R.J., and R. Rosenberg. 1995. Marine benthic hypoxia: A Review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology: An Annual Review* 33:245–303.

Dodds, W.K., et al. 1998. Suggested classification of stream trophic state: Distribution of temperate stream types by chlorophyll, total nitrogen, and phosphorus. *Water Research* 32(5):1455–62.

Dole, R.B. 1909. *The Quality of surface waters in the United States: Part I–Analysis of waters east of the one-hundredth meridian.* U.S. Geological Survey Water Supply Paper 236. Washington, DC: U.S. Government Printing Office. 123 pp.

Downing, John A., et al. 1999. *Gulf of Mexico hypoxia: Land and sea interaction,* Task Force Report No. 134. Ames IA: Council for Agricultural Science and Technology. 44 pp.

Jansson, Bengt-Owe, and Kristina Dahlberg. 1999. The environmental status of the Baltic Sea in the 1940s, today, and in the future. *Ambio* 28(4):312–19.

Jickells, T.D. 1998. Nutrient biogeochemistry of the coastal zone. *Science* 281:217–21.

Johansson, J.O.R., and H.S. Greening. 1999. Sea grass restoration in Tampa Bay: A Resource-based approach to estuarine management. In: *Sea grasses: Monitoring ecology, physiology, and management,* ed. S.A. Bortone, pp. 270–93. Boca Raton, FL: CRC Press.

Justić, Dubravko, et al. 1996. Effects of climate change on hypoxia in coastal waters: A Doubled CO_2 scenario for the northern Gulf of Mexico. *Limnology and Oceanography* 41(5):992–1003.

Justić, Dubravko, et al. 1997. Impacts of climate change on net productivity of coastal waters: Implications for carbon budgets and hypoxia. *Climate Research* 8:225–37.

Kunkel, Kenneth E., et al. 1999. Long term trends in extreme precipitation events over the conterminous United States and Canada. *Journal of Climate* 12:2515–27.

Leighton, M.O. 1907. *Pollution of the Illinois River by Chicago sewage.* U.S. Geological Survey Water Supply Paper 194. Washington, DC: U.S. Government Printing Office. 369 pp.

Meade, R.H., ed. 1995. *Contaminants in the Mississippi River.* U.S. Geological Survey Circular 1133. Washington, DC: U.S. Government Printing Office. 140 pp.

National Research Council (NRC). 1992. *Restoration of aquatic ecosystems.* Washington DC: National Academy Press. 552 pp.

National Research Council (NRC). 1993. *Managing wastewater in coastal urban areas.* Washington DC: National Academy Press. 477 pp.

Nixon, Scott W. 1995. Coastal marine eutrophication: A Definition, social causes, and future concerns. *Ophelia* 41:199–219.

Palmer, Arthur W. ca. 1903. *Chemical survey of the waters of Illinois: Report for the years 1897–1902.* Champaign, IL: University of Illinois. 254 pp.

Ryther, J.H., and W.M. Dunstan. 1969. Nitrogen, phosphorus and eutrophication in the coastal marine environment. *Science* 171:375–80.

Turner, R. Eugene. 1999. A Comparative mass balance budget (C, N, P and suspended solids) for a natural swamp and overland flow systems. In *Nutrient cycling and retention in natural and constructed wetlands,* ed. J. Vymazal, pp. 61–71. Leiden, The Netherlands: Backhuys Publishers.

U.S. Environmental Protection Agency (EPA). 1997. *Proceedings of the first Gulf of Mexico hypoxia management conference,* December 1995. Stennis Space Center, MS: Gulf of Mexico Program Office. 198 pp.

U.S. Geological Survey (USGS). 1999. *The Quality of our nation's waters: Nutrients and pesticides.* U.S. Geological Survey Circular 1225. Washington, DC: U.S. Government Printing Office. 82 pp.

Vitousek, Peter M., et al. 1997. Human alteration of the global nitrogen cycle: Sources and consequences, ecological applications. *Ecological Applications* 7(3):737–50.

World Bank. 1998. *World Development Indicators 1998.* Washington, DC. 388 pp.

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