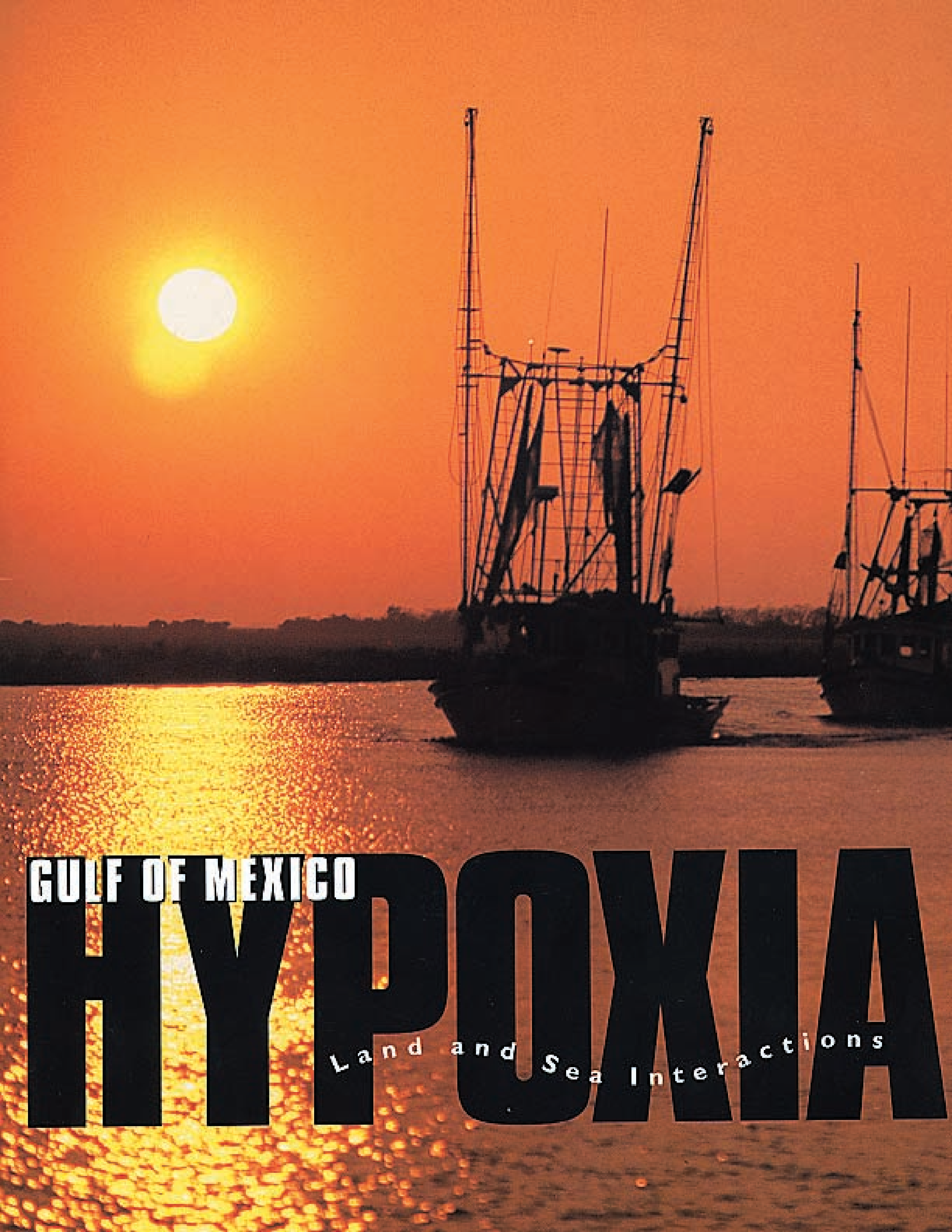

GULF OF MEXICO HYPOXIA

Land and Sea Interactions

Gulf of Mexico Hypoxia: Land and Sea Interactions

Council for Agricultural Science and Technology
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Task Force Report

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Council for Agricultural Science and Technology

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Foreword

Following a recommendation by the CAST National Concerns Committee, the CAST Board of Directors authorized preparation of a report on hypoxia in the Gulf of Mexico.

Dr. John A. Downing, Department of Animal Ecology, Iowa State University, Ames, served as chair for the report. A highly qualified group of scientists served as task force members and reviewers and participated in the writing and review of the document. They include individuals with expertise in agricultural economics, agricultural engineering, agronomy, animal ecology, biogeochemistry, biological sciences, environmental research, limnology, marine science, oceanography, and soil science.

The task force prepared an initial draft of the report. The reviewers reviewed the manuscript. The task force revised the document and reviewed the proofs. The CAST Executive and Editorial Review committees reviewed the final draft. The CAST staff provided editorial and structural suggestions and published the report. The authors are responsible for the report's scientific content.

On behalf of CAST, we thank the chair, authors, and reviewers who gave of their time and expertise to prepare this report as a contribution by the scientific community to public understanding of the issue. We also thank the employers of the scientists, who made the time of these individuals available at no cost to CAST. The members of CAST deserve special recognition because the unrestricted contributions that they have made in support of CAST also have financed the preparation and publication of this report.

This report is being distributed to members of Congress, the White House, the U.S. Department of Agriculture, the Congressional Research Service, the Food and Drug Administration, the Environmental Protection Agency, the Agency for International Development, and the Office of Management and Budget, and to media personnel and institutional members of CAST. Individual members of CAST may receive a complimentary copy upon request for a $3.00 postage and handling fee. The report may be reproduced in its entirety without permission. If copied in any manner, credit to the authors and to CAST would be appreciated.

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Managing Scientific Editor

Interpretive Summary

The Gulf of Mexico hypoxic zone, a bottom area with dissolved oxygen levels too low to sustain animal life, is the largest zone of anthropogenic, or human caused, coastal hypoxia in the Western Hemisphere. Many hypoxic zones elsewhere in the world have been caused by excess nutrients exported from rivers, resulting in reduced commercial and recreational fisheries. Hypoxic zones are now one of the most widespread, accelerating, human-induced deleterious impacts in the world's marine environments.

Characteristics of Gulf of Mexico Hypoxia

Mid-summer coastal hypoxia in the northern Gulf was first recorded in the early 1970s. Persistent coastal hypoxia has been most widespread during the 1990s. Hypoxic waters can include 20 to 80% of the water profile between 5 and 30 meters (m) water depth (16 to 100 feet [ft]), can stretch from the mouth of the Mississippi River beyond the Texas border, and can extend as far as 130 kilometers (km) (80 miles) offshore. The hypoxic zone covered 12,400 square kilometers (4,800 square miles) in 1998: about the size of Connecticut.

Causes of Gulf of Mexico Hypoxia

Gulf hypoxia results from

- decomposition of organic matter growth stimulated by Mississippi River nutrients and
- stratification of marine waters due to Mississippi River water inflow.

Spring and summer stratification caused by fresh river water flowing over saltier marine water impedes mixing of oxygen into deep waters. Organic matter produced in the surface waters of the Gulf in response to fertilization by excess nutrients from the Mississippi River settles to the bottom decomposing, using oxygen, and creating hypoxia.

Nitrogen (N) is the principal nutrient yielding excess organic matter sedimentation to the Gulf hypoxic zone. Nitrogen export from the Mississippi River Basin has increased 2- to 7-fold over the last century. Silicon (Si) and phosphorus (P) also play a role, and the changing balance of N, Si, and P can affect marine food chains. Freshwater flux and organic matter delivery by the Mississippi River may exacerbate hypoxia, but sedimentation of marine organic matter from increased river nutrients is the principal cause.

Social and Economic Dimensions of Hypoxia

Advanced anthropogenic hypoxia elsewhere in the world has had serious impacts on fisheries. Short-term economic costs impact

- commercial fishing,
- consumers of seafood,
- tourism,
- recreational fishing, and
- nonusers discouraged by perceived pollution.

Commercial and recreational fisheries in the Gulf generate $2.8 billion annually. Signs consistent with impact on Gulf of Mexico fisheries are

- reduced food sources for fish and shrimp in hypoxic areas,
- reduced abundance of fish and shrimp in hypoxic waters, and
- declines in shrimp catch and catch efficiency since hypoxia expanded.

Opportunism and adaptability of commercial fishing communities in the Gulf minimize economic impacts. Dozens of the world's hypoxic zones have already lost benthic, or bottom dwelling, organisms and key fishing industries.

Sources of Mississippi River Nitrogen

The majority of Mississippi River N originates from agricultural practice, while smaller fractions arise from human sewage, nonagricultural fertilizer use, and precipitation. The Mississippi River exports 1.8×10^9 kilograms (kg) (about 2 million short tons) of N each year. Agriculture's share is an average one ton of N for each of the million farms in the basin, or about 2 to 3 kg per agricultural hectare (2 to 3 pounds [lb]/acre). This lost N has a fertilizer value of about $410 million.

The Mississippi River Basin

- covers 41% of the contiguous United States,
- is home to 47% of the nation's rural population,
- generates 52% of U.S. farm receipts ($98 billion annually),
- comprises 52% of U.S. farms, and
- creates 33% of all U.S. farm-related jobs.

Nitrogen Export from Agricultural Landscapes

Nitrogen moves from agricultural land to surface waters by air, surface runoff, sediment transport, and subsurface drainage. Typical direct losses from agricultural lands are 3 to 20 kg/hectare (ha)/year (air), 1 to 50 kg/ha/year (surface runoff), and 2 to 130 kg/ha/year (subsurface drainage). Inexpensive management options can reduce N losses from agricultural lands, e.g., alterations of fertilizer application methods to decrease runoff losses, alterations of tillage regimes to decrease sediment bound nutrient transport, and fine-tuning application rates to decrease losses through subsurface drainage.

Aquatic Processing of Nutrient Flux

Uptake, adsorption, denitrification, and sedimentation in streams, wetlands, lakes, impoundments, and marshes also can reduce delivery of nutrients to the Gulf. Nitrogen removal rates are highest (> 50%) when N concentrations are moderate and waters move slowly. Riparian areas, wetlands, and other aquatic systems can slow water transport and decrease N flux.

Costs and Benefits of Decreasing Agricultural Nutrient Flux

Decreasing agriculture's contribution to Gulf of Mexico nutrients will require changes in crop and livestock management practices to reduce nutrient losses. Several benefits would accrue to agriculture and society:

- decreased risk to marine fishing communities,
- more efficient use of nutrients and energy,
- lower fertilizer costs,
- decreased health risk from contamination, and
- improved aquatic habitats and recreation.

Societal benefits of agricultural nutrient flux reductions can be very great.

Best management practices (BMPs) to reduce N flux are often as profitable as existing practices. Lack of producer familiarity with BMPs and risk aversion limit their use. The economic practicality of achieving substantial N flux reductions varies among cropping systems, but the social benefits substantially exceed the private costs. Comprehensive evaluation of costs and benefits of decreased nutrient flux to the Gulf should elucidate

- the agricultural N load reduction needed to assure water quality in the Gulf of Mexico,
- specific social and monetary costs and benefits of attaining those reductions, and
- the economic and social efficiency of decreased nutrient loads.

Future of Hypoxia in the Gulf of Mexico

Hypoxia from human nutrient activities has caused large-scale loss of marine resources around the world. Nutrient abatement in large systems has yielded slow recovery because of accumulated materials in sediments, but smaller systems recover rapidly. Large-scale agricultural nutrient abatement can be accomplished using current technology but will require improvements in nutrient retention by Mississippi River Basin agriculture.

Remediation programs elsewhere have shown

- marine degradation has occurred slowly so recovery is slow;
- multilevel, multi-institutional support is needed for effective nutrient management;

- large-scale ecosystem restoration is technically achievable;
- climate variability can mask restoration success; and
- the benefits of restoration will accrue to multiple facets of society.

Recommendations

- Control, retain, and monitor nutrients leaving agricultural and key Mississippi River Basin lands.
- Create, enhance, and distribute information on cost-effective agricultural nutrient management methods.
- Set and achieve goals of nutrient flux reduction tied to downstream water quality improvement.
- Seek cost-effective solutions to enhance the security of agricultural and coastal communities.
- Gauge effectiveness of solutions by societal and private costs and benefits.
- Implement policies favoring long-term, broad strategies that enhance life and environment in the Mississippi River Basin and the Gulf Coast.
- Monitor changes in hypoxia, its potential causes, and the impacts of marine eutrophication on society and environment.

1 Marine Hypoxia Worldwide

What is Hypoxia?

Oxygen is necessary to sustain animal life. In aquatic environments, dissolved oxygen serves the respiration needs of fish and invertebrates. Once dissolved into surface waters, oxygen usually is mixed throughout the water column, generally including bottom waters. When the supply of oxygen to the bottom is cut off or the consumption rate exceeds resupply, oxygen concentrations become too low to sustain animal life (Figures 1.1, 1.2, and 1.3). This state of low dissolved oxygen is known as hypoxia. Hypoxic waters are operationally defined as those in which dissolved oxygen levels fall below 2 to 3 milligrams (mg)/liter (L). When dissolved oxygen is below the level of 2 mg/L, fishing boats (mainly trawlers) do not capture any shrimp or demersal (bottom dwelling) fish in their nets (Leming and Stuntz, 1984; Pavela et al., 1983; Renaud, 1986b). The two principal factors that cause hypoxia are (1) water column stratification (lack of mixing) that isolates bottom water from surface air supplies and (2) decomposition of organic matter that uses up oxygen (Figure 1.4).

Figure 1.1. **Spider crab (*Libinia* sp.) suffocated by low oxygen, or hypoxia, in the Gulf of Mexico. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.**

Worldwide Dimensions of Hypoxia

The problems the Gulf of Mexico faces from hypoxia are not unique. Hypoxia related to human activities currently threatens many of the major coastal embay-

Figure 1.2. **Juvenile portunid crab (*Portunus* sp.) suffocated by hypoxia in the Gulf of Mexico. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.**

Figure 1.3. **A fish kill on Chesapeake Bay in the United States. Photograph courtesy of Chesapeake Bay Program, U.S. Environmental Protection Agency, Annapolis, Maryland.**

ments and estuaries in the world (Figure 1.5) (Diaz and Rosenberg, 1995). Common elements found in most of these ecosystems are a reported increase in nutrient concentrations and a decline in dissolved oxygen levels, both beginning in the 1940s or 1950s (Diaz and Rosenberg, 1995). Some areas are naturally hypoxic, e.g., the upwelling zones on the western edge of continents (the Peru upwelling being one of the most famous), fjord systems, and the deep central basin of the Black Sea. In most hypoxic zones, however, a strong correlation exists between human activities and declining dissolved oxygen, e.g., the northern Adriatic Sea, Italy-Croatia; Kattegat, Sweden-Denmark. In others, the linkage of hypoxia and human activities is more complex and therefore more difficult to discern, e.g., the Chesapeake Bay.

Up to the 1950s, reports of mass mortality of marine animals caused by hypoxia were limited to systems that already had histories of oxygen stress, such as “jubilees” in Mobile Bay, Alabama, first reported in the 1860s. (A jubilee is the crowding of fish, shrimp, and crabs onto a beach from deeper hypoxic waters pushed onshore because of wind shifts.) Starting in the 1960s, there was a dramatic increase in the number of systems reporting hypoxia-related problems for the first time. By the end of the 1980s, virtually every major coastal embayment was reporting serious environmental problems related to hypoxia. In the 1990s, many systems continue to report expanding problems with hypoxia. For example, every major

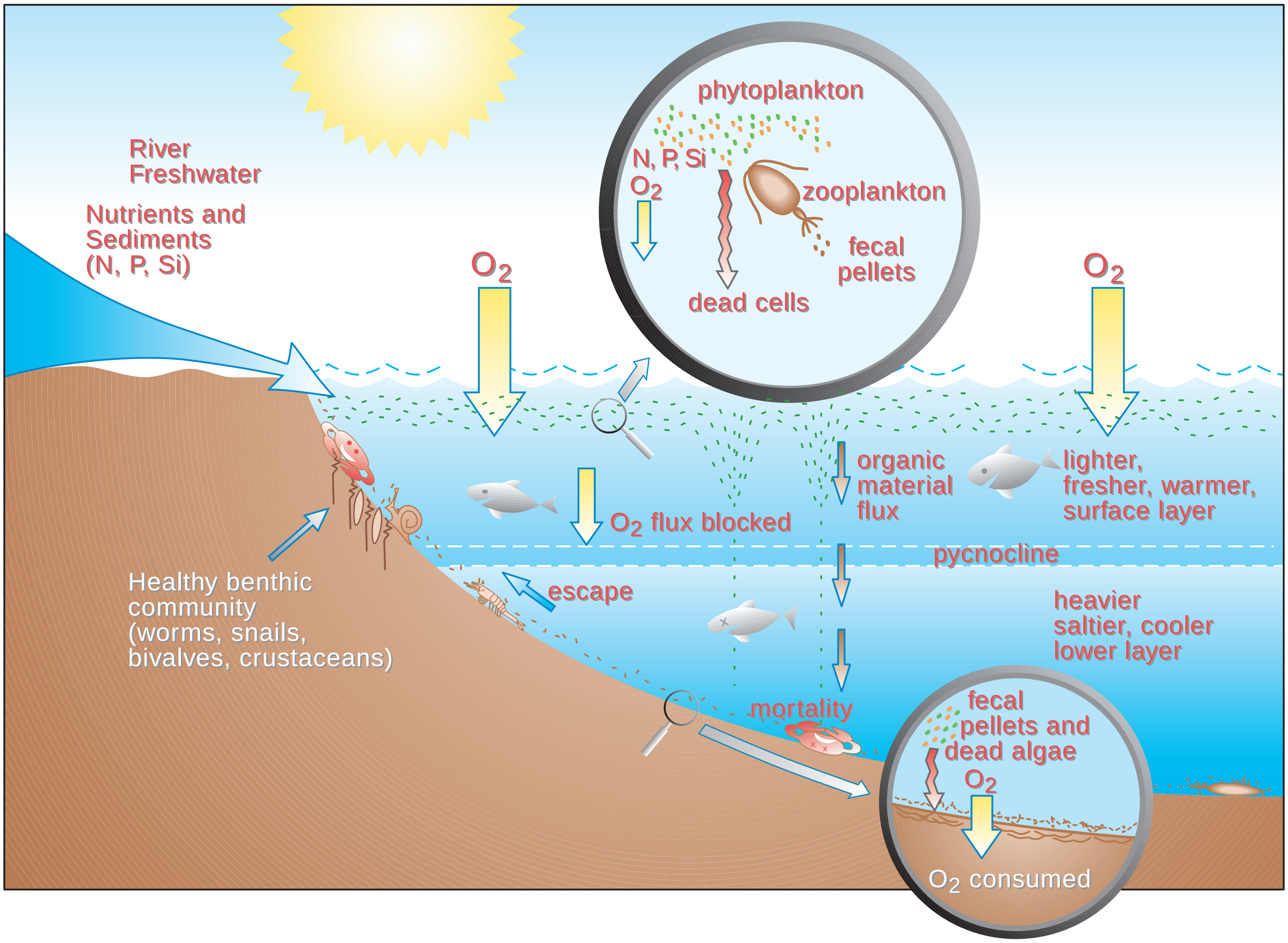

Figure 1.4. The hypoxic zone in the Gulf of Mexico arises because nutrients from the Mississippi River Basin fuel excess marine primary production that falls to the bottom and decomposes in the denser, saltier lower layer of the sea. Decomposition consumes oxygen in the lower layer that cannot be renewed from surface waters because of strong stratification of fresh and salt water. Oxygen consumption decreases dissolved oxygen levels to below the concentrations needed to sustain marine life.

embayment in Japan currently has serious hypoxia problems that impact bottom fisheries. An evaluation of all these systems (Diaz and Rosenberg, 1995) points to a scenario that plays out as follows:

1. Human development associated with population increases within the watershed alters land-use patterns.
2. Runoff and point discharges increase nutrients delivered to the marine system.
3. Self-regulatory and assimilative processes within the system can at first compensate for increased primary production resulting from extra nutrients, but become overloaded.
4. Finally, the onset of hypoxia occurs after organic matter produced as a result of extra nutrient loads sinks to the bottom to decompose and consumes more oxygen than can be resupplied.

Hypoxia Is Linked to Nutrients and Eutrophication

Increasing human-related input of nutrients to many coastal areas is the main contributor to recent world increases in hypoxia (Diaz and Rosenberg, 1995). Many studies have demonstrated a correlation through time between population growth, increased nutrient discharges to marine waters, increased primary production in coastal areas, and increased occurrence of hypoxia (Justi et al., 1987). The Gulf of Trieste in the northern Adriatic Sea is a good example of this connection, where a long-term data set on this urbanized area illustrates the link between urban (56%) and agricultural (38%) nutrients and hypoxia (Marchetti et al., 1989; Provini et al., 1992). Measurements from the early twentieth century indicate that oxygen concentrations in bottom waters were high year-round. The current severe annual hypoxia in this region was reached over a period of about 25 years (from about 1955 to 1980) and is a direct result of increased organic matter sedimentation from algae blooms fueled by excess nutrients from Italy's Po River.

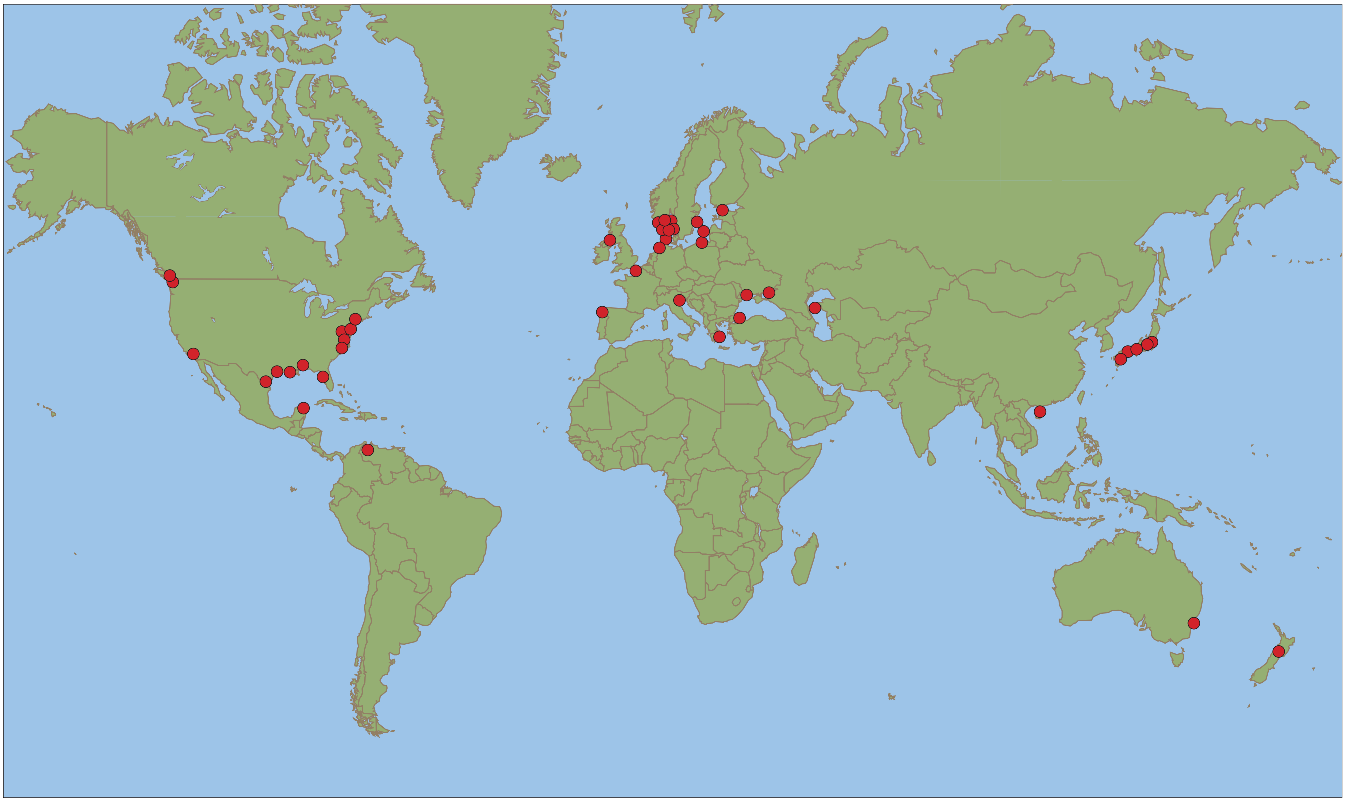

Figure 1.5. Major eutrophication-induced hypoxic zones of the world. Most of these hypoxic zones are found in regions receiving large riverine inputs of anthropogenic nutrients. A few natural hypoxic zones are not indicated (derived from Diaz and Rosenberg, 1995).

2 Dimensions and Characteristics of Gulf of Mexico Hypoxia

Description

The inner- to mid-continental shelf of the northern Gulf of Mexico, from the Mississippi River delta westward and onto the upper Texas coast, is now the site of the largest zone of anthropogenic coastal hypoxic bottom water in the Western Hemisphere (Figure 2.1). It coincides with some of the nation's most important fishing waters. The area covered by the Gulf of Mexico hypoxic zone during mid-summer surveys taken from 1993–1998 (approximately 12,400 square kilometers [km^2] to 18,000 km^2) (Figure 2.2) makes it the third largest coastal hypoxic area, after the Baltic Sea and the northwestern shelf of the Black Sea. In 1998, the Gulf hypoxic zone was about the size of Connecticut.

Gulf hypoxic waters are distributed from shallow depths near shore (4 to 5 meters [m]) to as deep as 60 m (Rabalais et al., 1991, 1998). During certain wind conditions, hypoxic water masses move and impinge on barrier island shores, forcing fish and shrimp to concentrate inshore and causing localized periodic fish kills reported widely by regional newspapers. Hypoxia occurs not only at the bottom near the sediments but well up into the water column. Hypoxia normally covers 20 to 50% of the total water column but, under some conditions, may encompass over 80% (Figure 2.3). Usually, hypoxic bottom waters are found between 5 and 30 m, extending from as little as 55 km from shore on the steeply sloped southeastern Louisiana shelf to as much as 130 km offshore along the more gradual slopes of the central and southwestern Louisiana shelf. Throughout its distribution, the impact of hypoxic bottom waters is exacerbated by the release of toxic hydrogen sulfide from sediment (Harper et al., 1991).

Hypoxia was first recorded on the continental shelf of the northern Gulf of Mexico in the early 1970s during environmental assessments of oil production and studies examining the development of transportation in the Gulf. Following the initial documentation of hypoxia on the southeastern Louisiana shelf in 1972–1974, studies in 1975–1976 (Ragan et al., 1978; Turner and Allen, 1982) and further environmental assessments revealed midsummer low oxygen conditions in many inner-shelf areas. Consistent data collection on the distribution and dynamics of hypoxia began in 1985 (Rabalais et al., 1991). Prior to the 1970s, only

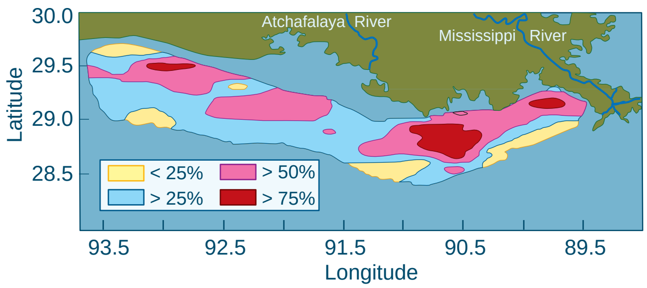

Figure 2.1. Map of the Louisiana coast showing areas where mid-summer hypoxia occurs most frequently. The map is approximately 275 miles wide (the distance from Des Moines to Chicago) (unpublished data from Rabalais, Turner, and Wiseman). The colored areas, i.e., < 25%, > 25%, > 50%, > 75%, indicate the frequency of occurrence of hypoxia during mid-summer of 1985–1997. The sampling grid has been held as constant as possible since 1985.

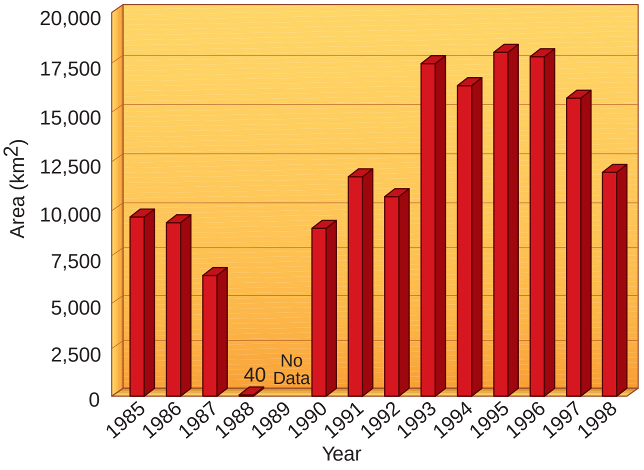

Figure 2.2. Changes in the estimated bottom area covered by the Gulf of Mexico hypoxic zone since routine monitoring began (modified from Rabalais et al., 1998).

scattered anecdotal data from shrimp trawlers in the 1950s and 1960s reported low or no catches, and the “dead” or “red” water consistent with low oxygen conditions. Analyses of the sedimentary record (discussed on page 10) show that severe hypoxia is a recent development in Gulf waters.

Maps of the extent of hypoxia in midsummer provide a benchmark for year-to-year comparisons. The persistence of these areas, however, is not known, because of the high cost of mapping hypoxia throughout the year (Figure 2.4). Weekly shelfwide cruises in 1993 and 1994 indicated that the large size of the hypoxic zone persisted over 2- to 3-week periods but varied somewhat in configuration. Figure 2.1 shows areas in the Gulf of Mexico where mid-summer hypoxia occurs most frequently. Monthly surveys on the southeastern Louisiana shelf show that critically depressed dissolved oxygen concentrations occur in the underlying saline waters of the Gulf nearly continuously from mid-May through mid-September and from as early as late February through early October. From March through May, hypoxia is often patchy and ephemeral; it is most widespread, persistent, and severe from June through August (Rabalais et al., 1991). The summer low oxygen water mass moves and changes shape in response to winds, currents, and tidal flow. This can be likened to a large cloud of air with decreased oxygen stretching from Des Moines to Chicago that moves and changes configuration in response to wind.

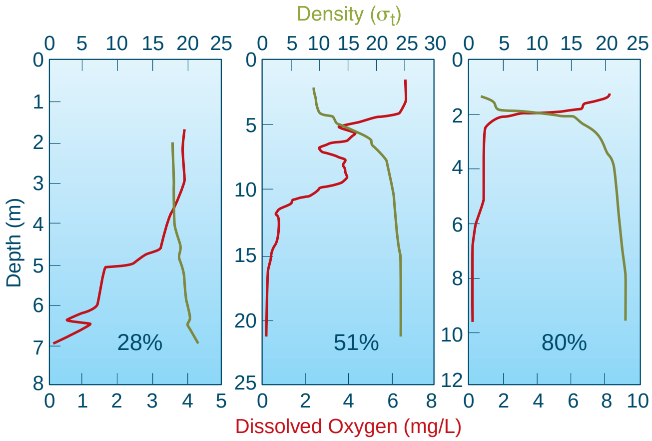

Figure 2.3. **Typical summer oxygen profiles of the Gulf of Mexico (July 24–26, 1993). Low-density water signifies freshwater input of the Mississippi River (unpublished data from Rabalais, Turner, and Wiseman). The percentage noted on each panel indicates the fraction of the total water column that was hypoxic on these dates.**

Figure 2.4. **Deploying conductivity, salinity, temperature, dissolved oxygen, and depth (CTD) meter in hypoxia research. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.**

Causes of Gulf of Mexico Hypoxia

The best scientific evidence points to two principal factors that lead to the development of hypoxia in the Gulf of Mexico: (1) decomposition of organic matter that is formed in response to nutrient enrichment (Figures 2.5, 2.6, and 2.7) and (2) water column freshwater/saltwater stratification. The northern Gulf of Mexico is strongly influenced by the Mississippi and Atchafalaya Rivers, whose combined discharges account for 60% of the Gulf’s freshwater input (Howarth et al., 1996) (Figure 2.8). Spatial and temporal variability in the distribution of hypoxia is related to the amplitude and phasing of the Mississippi River discharge and nutrient flux (Justi*f* et al., 1993; Pokryfki

Figure 2.5. **Dr. Donald E. Harper, Jr., Texas A&M University, Galveston, Texas, photographs dead organisms on the bottom of Gulf of Mexico, which were killed by bacteria (*Beggiatoa*) that grow in low oxygen areas. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.**

and Randall, 1987; Rabalais et al., 1996; Wiseman et al., 1997). Because freshwater inputs to the sea float over denser salt water, water column stratification is strong in spring when runoff and river flow are high and continues during the summer when warm weather sets up thermal stratification (Rabalais et al., 1991). Hypoxia is most intense during these periods (Rabalais et al., 1991) because strong stratification prevents oxygen from being mixed into deeper waters. A strong, near-surface freshwater/saltwater boundary, or pycnocline, is a necessary condition for hypoxia to occur, while a weaker, seasonal pycnocline guides the shape of the hypoxic zone (Wiseman et al., 1997). Winds sufficient to vertically mix the water column decrease the intensity of freshwater/saltwater stratification as well as mix aerated waters from the surface with those of the bottom layer (Rabalais et al., 1992b, 1994).

Nutrients delivered by rivers support high primary production of plankton in the immediate and extended plume of the Mississippi River (Lohrenz et al., 1990, 1994, 1997; Sklar and Turner, 1981). Small-scale and short-term variability in productivity derives from turbidity, nutrient concentrations, temperature, and salinity (Lohrenz et al., 1990, 1994). Maximal development of algal biomass (Turner and Rabalais, unpublished data) and rates of primary production (Lohrenz et al., 1990) typically are observed at intermediate salinities and coincide with biological uptake of nutrients from inflowing, nutrient-rich river water. Patterns of nutrient depletion provide evidence that riverine inputs of dissolved inorganic N ultimately determine the extent of river-enhanced productivity and biomass.

Figure 2.6. Dr. Donald E. Harper, Jr., Texas A&M University, Galveston, Texas, collects a sample of bacterial material from the bottom of the Gulf of Mexico. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.

Flood and drought observations support a strong connection between river nutrients and hypoxia. Natural variability in river flow through periods of drought and flood (1985–1998) illustrates the response of the Gulf to impacts of freshwater and nutrients. From 1985 to 1992, the configuration of the hypoxic zone was usually one of discontinuous areas situated west of the Mississippi and Atchafalaya River deltas. Its size averaged 7,000 to 9,000 km^2 (Figure 2.2). Since the 1993 Mississippi River flood, when nutrient export was drastically increased, bottom water hypoxia has been twice as extensive, estimated to be between 16,000 to 18,000 km^2 in 1993-1997 (Dowgiallo, 1994; Rabalais et al., 1998). Higher streamflows in 1993 resulted in decreased surface salinities and temperatures; increased nutrient loading, phytoplankton counts, and carbon flux; and decreased oxygen content of the lower water column (Rabalais et al., 1998). Although river freshwater and nutrient fluxes were more "normal" in 1994, the area covered by the midsummer hypoxic zone did not decline. More organic matter was predicted by Justi*f* et al. (1997) for burial and accumulation in the sediments following the 1993 hypoxic season, which could account for the sustained large size beyond 1993. Along with residual effects of the 1993 flood, differences in

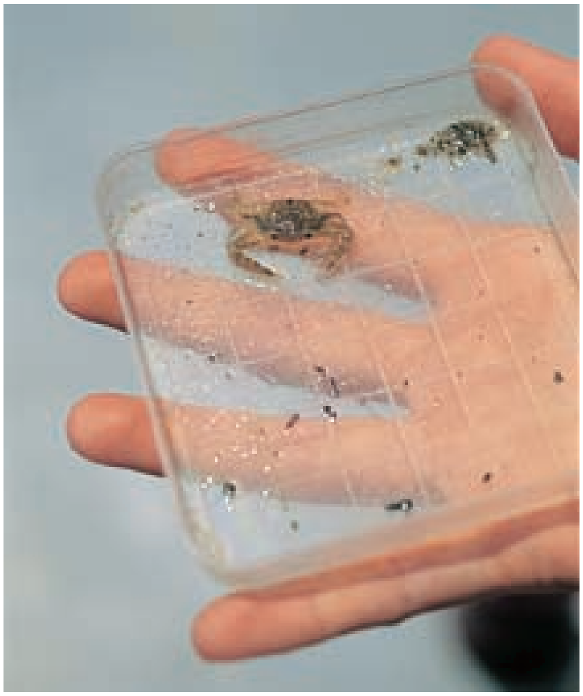

Figure 2.7. Dead portunid crab (*Portunus gibbesii*) collected in sediment sample, which was suffocated by hypoxia. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.

timing of peak flow or increased flow or both from 1994 to 1997 likely affected the sustained large size of the hypoxic zone. Different oceanographic conditions coupled with a "normal" flow year in 1998 were followed by a smaller bottom areal size. The estimated area of bottom influenced by hypoxia derived from a single 5-day cruise in mid-summer should not be over-interpreted in making year-to-year comparisons. Clearer linkages between river discharge and nutrient flux are available from monthly transects on the southeastern shelf and long-term trends seen in the sedimentary record.

Another example illustrates the importance of nutrient loads for fueling hypoxia and freshwater/saltwater stratification for maintaining it. A 52-year low river flow of the Mississippi River in 1988 was associated with the late-summer disappearance of hypoxia. Although that year's seasonal flow sequence began normally, with spring nutrient input establishing the usual June hypoxic zone, river flow fell to record low levels, so hypoxia was not maintained without continued freshwater input.

Nitrogen is the river-borne nutrient most relevant to phytoplankton production in the broad marine region contributing to hypoxia. Primary production on the southeastern Louisiana shelf correlates strongly with dissolved inorganic N concentration and flux and with orthophosphate concentration (Lohrenz et al., 1997). Evidence from long-term data sets (Turner and Rabalais, 1994b) and histories provided by analysis of sediment deposits (Eadie et al., 1994; Turner and Rabalais, 1994a) demonstrate that increases in riverine dissolved inorganic N loads correlate with anthropogenic nutrient enrichment leading to eutrophication of the continental shelf waters.

Sediments accumulating under the plume of the

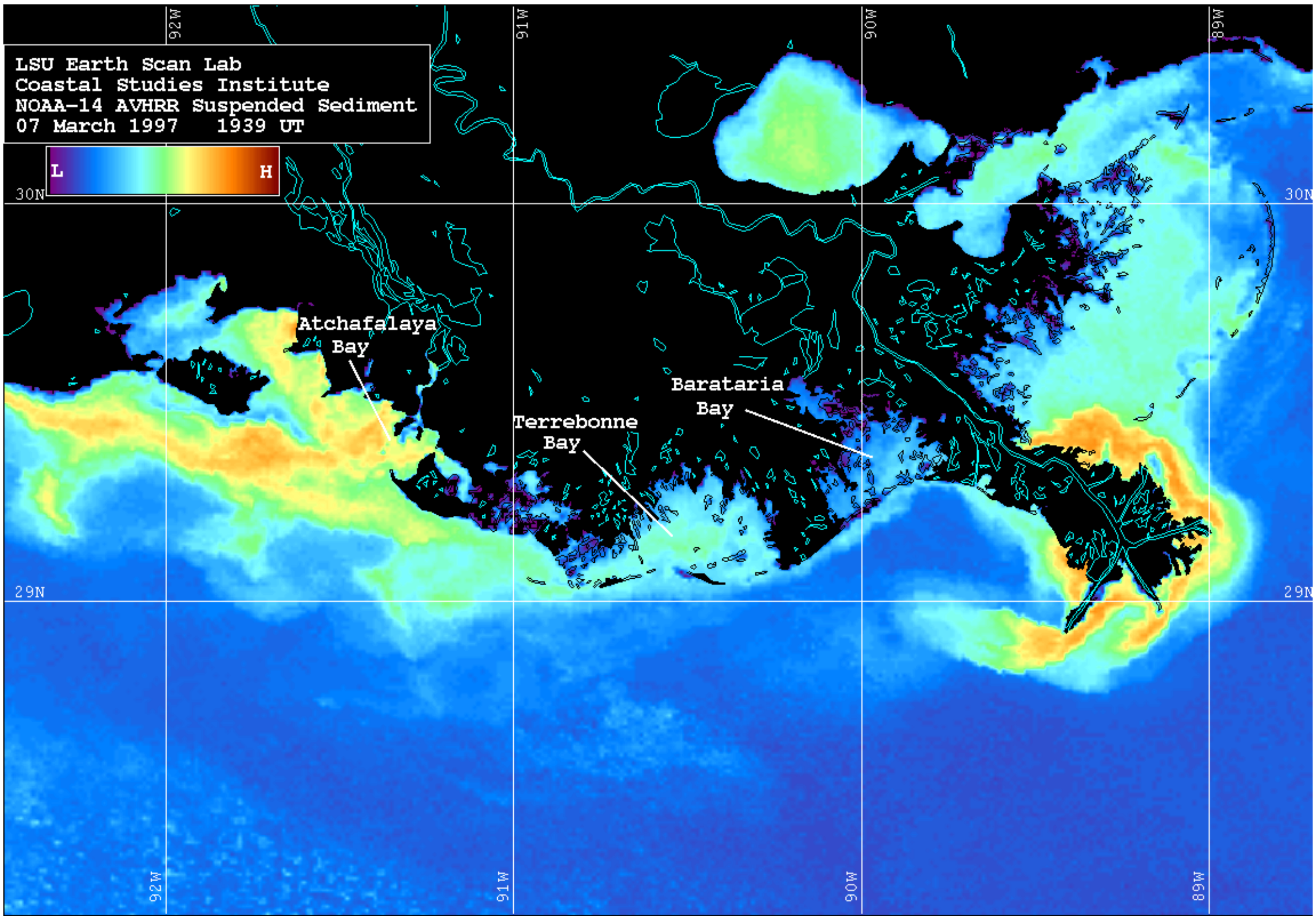

Figure 2.8. A National Oceanic and Atmospheric Administration AVHRR reflectance image of the Atchafalaya and Mississippi river plumes entering the Gulf of Mexico. The orange tones show regions of highest backscattering due to high concentrations of suspended sediments. The blue tones indicate areas of little scattering, therefore, low sediment levels at the surface. Image courtesy of Dr. Nan D. Walker, Louisiana State University, Baton Rouge, Louisiana.

Mississippi River provide historical information about changes in nutrient loading beyond those obtained from actual hydrographic data. Sediments deposited on the bottom surface directly downstream and beneath the surface river plume reflect the in situ primary production and subsequent transport of organic carbon from surface to bottom waters (Rabalais et al., 1992a; Turner and Rabalais, 1994a). Biogenic silica (BSi) in sediments is an indicator of the structural remains of diatoms sequestered in sediments. Relative changes in the biogenic silica content of the sediments (% BSi) have been shown to be an accurate gauge of in situ diatom production (Conley et al., 1993). The % BSi in dated sediment cores shows historically increasing trends that parallel the documented increases in N loading from the Mississippi River, even though over the same period the river-borne silicate concentrations have been decreasing (Turner and Rabalais, 1994a) (Figure 2.9). This sedimentary record provides direct evidence for an increase in the flux of algae such as diatoms from surface to bottom waters beneath the Mississippi River plume. The increased % BSi deposition represents a significant change in marine-origin carbon deposition rate (as much as 43% higher after 1980 than from 1900 to 1960). These results are corroborated by the same rate of increase in marine-origin carbon in sediment cores collected from the continental shelf where the Mississippi River empties into the Gulf of Mexico (Eadie et al., 1994). Protozoans of the order Foraminifera that produce calcium carbonate cell walls, also have been used as indicators of decreased oxygen levels and/or carbon-enriched sediments (Nelsen et al., 1994; Rabalais et al., 1996; Sen Gupta et al., 1996). Foraminifera records in dated sediment cores reveal a strong increase in oxygen stress over the last 100 years, especially since the 1950s. The sedimentary record documents eutrophication and increased marine-origin organic sedimentation in bottom waters that are positively correlated with increasing N loads and oxygen stresses.

Although much of the debate surrounding hypoxia has centered upon N as the major nutrient involved in hypoxia, other nutrients exported from the Mississippi River Basin are also involved. Shifts in the export of other elements such as dissolved Si and phosphorus (P) can exacerbate the problem and lead to noxious algal growth. This is important because diatoms, a group of algae particularly important to marine food chains, require a high ratio of Si to N in their nutrient supply, i.e., above 1:1 in molar units. During the twentieth century, the dissolved Si:N ratios in the lower Mississippi River have changed from approximately 4:1 to 1:1 (Rabalais et al., 1996; Turner and Rabalais, 1991). The decrease in relative abundance of Si in Mississippi River water favors phytoplankton algae other than diatoms. Non-diatom algae may be less useful in marine food chains (Justi*f* et al., 1995a, 1995b). Therefore, N and P may be less limiting to phytoplankton growth than historically, while Si limitation is now more probable. Coastal phytoplankton productivity has increased due to enriched nutrient conditions. This change is accompanied by an increasing incidence of noxious phytoplankton blooms from the relative paucity of dissolved Si (Dortch et al., 1997). These algae are generally less edible by zooplankton than the diatoms that are readily cycled through zooplankton to shrimp and other resource organisms. We as yet know little about the biogeochemistry of Si or P in the Mississippi River Basin.

Because stratification of the water column is important to the development and persistence of hy-

Figure 2.9. **Dr. Nancy N. Rabalais, Louisiana Universities Marine Consortium, Chauvin, Louisiana, extrudes sediment core samples. Photograph by Franklin J. Viola, Viola Photo Visions, Inc., Roswell, Georgia.**

poxia, it has been suggested that hypoxia has increased in response to long-term increases in water flow, not nutrients. However, the Mississippi River's discharge has increased only slightly since the 1900s, while N flux has increased more. The flow allocation between the Mississippi River proper and the Atchafalaya River has been maintained by the U.S. Army Corps of Engineers according to congressional mandate. Since 1820, the average annual discharge rate (decadal time scale) for the lower Mississippi River has been nearly stable (near 14,000 m^3/second [sec]), with a decrease during the 1950s and 1960s (Bratkovich et al., 1994). The riverine flow delivered to the shelf waters adjacent to Atchafalaya Bay has slowly increased, as has the combined flow delivered to the shelf region, more notably over the past two decades (Bratkovich et al., 1994). However, the effect of delivery of water to the Gulf through the Atchafalaya River would occur on the southwestern, not the southeastern, shelf, and the season of increased flow (fall) make these inputs inconsequential to the development of hypoxia. Thus, long-term biological responses in the surface waters near the Louisiana coast probably are not due to changes in amount or distribution of freshwater runoff and resulting stratification, but rather due to changes in water quality.

Fixation of carbon by photosynthesis in surface waters eventually contributes to high rates of organic carbon flux to the bottom (Qureshi, 1995; Redalje et al., 1994). The high particulate organic carbon flux fuels hypoxia in the bottom waters below the seasonal pycnocline (Justi*ƒ* et al., 1996; Qureshi, 1995). Seasonal variations in sedimentation of marine-generated organic matter are positively correlated with high surface water productivity and high discharge of the Mississippi River (Qureshi, 1995). Hypoxia is thus strongly related to Mississippi River nutrient flux discharge, primary production, and carbon flux (Justi*ƒ* et al., 1993, 1997; Pokryfi and Randall, 1987).

Although the Mississippi River discharges organic material (Turner and Allen, 1982) and decomposition of some this organic matter could consume marine oxygen, the major source of organic matter reaching the bottom waters of the northern Gulf of Mexico near the hypoxic zone is from marine phytoplankton production fueled by riverine nutrients (Rabalais et al., 1992a; Turner and Rabalais, 1994a). Suspended sediment from the Mississippi River has declined by about half since the 1950s (Meade, 1995), so oxygen consumption due to decomposition of the allochthonous, or transported, organic matter in suspended sediments has probably declined in importance. Sediment and carbon flux have decreased in part due to improved soil erosion control and constructed levees that now line the entire river, while dams on major tributaries such as the Missouri and Arkansas rivers have decreased the amount and size of sediments transported by the river. Revetments along banks of river channels have decreased lateral migration, bank caving, erosion, and other sources of sedimentary organic material. Cutoffs have also shortened the length of the river by about 240 km (150 miles). Keown et al. (1986) showed that since 1850 the suspended sediment load of the Mississippi River has declined by more than 70%. The load declined by 43% from the historic (prior to 1900) to the pre-dam period (1930–1952) and by 51% from the pre-dam to the post-dam period (Keown et al., 1986). Thus, modern increases in hypoxia cannot be attributed to particulate or dissolved organic flux in the Mississippi River.

Nutrient ratios of material flux from the Mississippi River also indicate that direct contributions of organic matter could account for much less of the sedimented carbon than marine phytoplankton production fueled by Mississippi River nutrients. Sedimenting marine phytoplankton generally have C:N ratios (as atoms) of 9.5–9.9:1 (Meybeck, 1982), whereas the C:N ratio of Mississippi River flux is about 2.3–3.7:1 (Howarth et al., 1996; Leenheer, 1982; Meybeck, 1982; Telang et al., 1991; Trefry et al., 1994). Therefore, between 2.7- and 4.3-times as much organic matter (on average) could be supplied to marine hypoxic zones by marine algae grown with Mississippi River N than could be supplied directly by riverine organic matter. Freshwater flux from the Mississippi River has remained relatively constant since the 1940s (Meade, 1995), suspended carbon loads in the Mississippi River have declined (Turner and Allen, 1982), while N exports have increased substantially (e.g., Turner and Rabalais, 1994a). Therefore, freshwater flux and sediment delivery may exacerbate hypoxia, but several lines of evidence show that sedimentation of marine organic matter resulting from increased river nutrients plays a pre-eminent role.

Changes in Nutrient Supply to the Gulf of Mexico

Because hypoxia in the Gulf is influenced by nutrient and water input from the Mississippi River, recent changes in nutrient flux are likely to have impacted the size and persistence of hypoxic waters. Although current N export rates of the Mississippi River Basin, expressed on a per unit land-area basis, are large compared to other world rivers (Howarth et al., 1996; Turner and Rabalais, 1991), rivers are normally significant sources of nutrient supply to the sea. Widespread hypoxia suggests that nutrient loads carried by the Mississippi River have increased greatly over the last 50 years.

Detailed N export data on the Mississippi River have not been collected as systematically as they have on Italy's Po River, which has a record of water clarity and nutrient data dating to the early part of this century (see Chapter 1). Although enough solid data on the Mississippi River exist to document changes since the 1950s (Turner and Rabalais, 1991), one way to determine how N flux from the Mississippi River Basin to the Gulf of Mexico has changed since human development began is to measure N export rates from watersheds that are similar to predevelopment conditions. Biogeochemists have estimated that the N flux from minimally disturbed ecosystems across various regions ranges between 0.76 kg/hectare[ha]/year and 2.3 kg/ha/year (Howarth et al., 1996). Export rates from undisturbed prairie lands, such as those found throughout much of the predevelopment Mississippi River Basin, are even lower, averaging 0.16 kg/ha/year (Dodds et al., 1966). In the early 1950s, the N export rate of the Mississippi River Basin was 0.66 kg/ha/year (Turner and Rabalais, 1991). Total N export from the Mississippi River Basin before human habitation might have been as low as 0.16 kg/ha/year but was unlikely to have been more than about 1.0 kg/ha/year. Current rates of N export from the Mississippi River Basin are about 5.7 kg/ha/year (Howarth et al., 1996; Turner and Rabalais, 1991). Nitrogen export rates from the Mississippi River Basin have therefore increased two- to seven-fold over the last century.

3 Social and Economic Dimensions of Marine Hypoxia

Introduction

Anthropogenic hypoxia has been shown to have important economic impacts on fisheries throughout the world (Caddy, 1993). Costs of environmental degradation can be both monetary and nonmonetary and can be expressed over short and long terms. Little is known about the nonmonetary costs of Gulf hypoxia or how long economic costs may continue even if eutrophication of the Gulf of Mexico is diminished. The short-term economic cost of fishery habitat destruction can impact several groups, including commercial fishing communities and industries, consumers of commercial fishery resources, the tourism industry, recreational fishing interests, and even those who choose not to use potentially impacted habitats for commercial or recreational activities (Lipton and Strand, 1997). Estimates of the economic value that people place on a healthy ecosystem (existence value) and economic losses from non-use and degraded quality of the resource (which impacts demand) are difficult to estimate but are probably serious (McConnell and Strand, 1989). Examples of fisheries collapse from increased nutrient flux elsewhere in the world (Table 3.1) suggest how great an economic threat hypoxia can become.

Worldwide Impacts on the Benthos and Fisheries

Hypoxia stress has had a devastating effect on fisheries in other ecosystems. Many seem to be near or at a threshold of imminent collapse, e.g., loss of fisheries and loss of biodiversity. The northern Gulf of Mexico may be typical of these ecosystems that are currently severely stressed by annual hypoxia. Under a scenario of increased or continuing nutrient flux, the future course of Gulf fisheries might be extrapolated from experience on the Black Sea's northwest continental shelf. Since the 1980s, increasing hypoxia has been blamed for the replacement of highly valued demersal, or bottom dwelling, fish species by less-desirable fish that are planktonic omnivores. Of the 26 commercial species harvested in the Black Sea during the 1960s, only six still support viable fisheries.

Hypoxia in the central Baltic also has led to degraded fisheries. Hypoxia began forming in deep waters (over 250 feet or 76 m) during the early 1950s. By the 1970s, many areas were affected by hypoxia year-round and bottom fish were no longer present. Currently, the area of permanently hypoxic water is over 100,000 km^2. Hypoxia is expanding into shallower water, severely decreasing spawning habitat for the important cod fishery. Negative impacts of anthropogenic hypoxia on fisheries around the world are listed in Table 3.1.

Impacts of Gulf Hypoxia

The potential social impact of hypoxia can be projected in short-term economic terms when one considers that hypoxia has led to complete loss of commercial and recreational fisheries in other nations (Table 3.1). Louisiana leads the Gulf of Mexico region in production and landing of commercial and recreational marine resources (Figure 3.1). These fishery resources are among the most valuable in the United States. For example, Louisiana's commercial shrimp fishery lands 33% of the nation's total catch and nearly 40% of the catch in the Gulf of Mexico (Figure 3.2). Just as

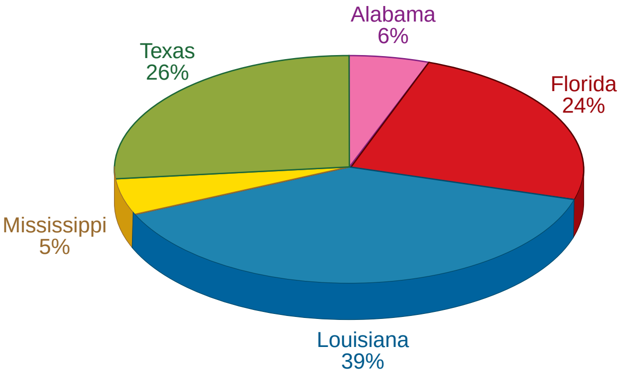

Figure 3.1. **Commercial fishery value by state for the Gulf of Mexico during 1996. Total value of yield for all states was approximately $690 million (Zimmerman, pers. com., 1998).**

important are Louisiana's recreational fishery resources, that are renowned for their magnitude and variety. Millions of fish are landed recreationally including scores of snapper, flounder, mackerel, tuna, jack, porgy, grunt, mullet, shark, sea bass, trigger fish, file fish, and dolphin fish (Mahi-Mahi). Recreational landings in 1996 were led by red drum, spotted sea trout, sheepshead, black drum, red snapper, sand sea trout, southern flounder, and Atlantic croaker. Gulf commercial landings of fish and shellfish have an annual dockside value of about $700 million (approximately $1.4 billion when processed), while recreational and commercial fisheries together generate around $2.8 billion per year (Holiday and O'Bannon, 1997).

Louisiana's commercial and recreational fisheries depend on species that have part of their life cycles

Table 3.1. Summary of hypoxia effects for systems where anthropogenic hypoxia has occurred (after Diaz and Rosenberg, 1995)[a]

System	Hypoxia level	Time trends	Benthos response	Fisheries response
North America				
Hillsborough Bay, Florida	Severe	NA	Mass mortality	NA
Long Island Sound, New York	Severe	+	?	Lobsters displaced
Louisiana Shelf	Mod./Severe	+	Mortality	Stressed
Main Chesapeake Bay, Maryland	Severe	+	Mortality	Stressed
Mobile Bay, Alabama	Severe	0	Mass mortality	Stressed
Pamlico River, North Carolina	Severe	NA	Mass mortality	NA
Perdido Bay, Florida	Severe	NA	Mass mortality	NA
Saanich Inlet, British Columbia	Mod./Severe	0	Mortality	NA
Europe				
Århus Bay, Denmark	Severe	+	Mass mortality	NA
Baltic Sea, Central	Persistent	++	No benthos	Only pelagic fishery remains
Bornholm Basin, S. Baltic	Mod./Severe	+	Mass mortality	NA
German Bight, North Sea	Severe	+?	Mortality	Stressed
Gullmarsfjord, Sweden	Severe	+	Mass mortality	Stressed
Kattegat, Sweden-Denmark	Mod./Severe	++	Mass mortality	Collapse of Norwegian lobster fishery
Kiel Bay, Germany	Severe	+	Mass mortality	Stressed
Laholm Bay, Sweden	Severe	++	Mortality	Stressed
Limfjord, Denmark	Severe	+	Mass mortality	No bottom fishery
Lough Ine, Scotland	Severe	0	Mass mortality	NA
Oslofjord, Norway	Mod./Severe	+	Mortality	Reduced
Swedish west coast fjords	Severe	++	Mortality	Stressed
Mediterranean				
Aegean Sea	Severe	?	?	NA
Black Sea (except N.W. shelf)	Persistent	+	No benthos	Pelagic fishery only
Black Sea N.W. Shelf	Severe	++	Mass mortality	Collapse of bottom fishery
Elefsis Bay, Aegean Sea	Severe	NA	Mass mortality	NA
Gulf of Trieste, Adriatic	Severe	++	Mass mortality	Stressed
Sea of Azov	Severe	+	Mass mortality	Reduced
Austral-Asia				
Seto Inland Sea, Japan	Moderate	–	Mortality	Reduced
Tome Cove, Japan	Severe	NA	Mortality	Reduced
Japan, all other harbors	Severe	++	Mass mortality	Reduced
Port Hacking, Australia	Severe	NA	Mortality	NA
Tolo Harbor, Hong Kong	Severe	NA	Mass mortality	NA

[a] Levels of hypoxia are "Moderate" (oxygen decline to about 0.7 mg/L), "Severe" (oxygen decline to near-anoxic levels, could also become anoxic); and "Persistent" (oxygen levels continuously low). Time trends indicate changes in the severity or area covered by hypoxia: "–" = improving conditions; "+" = gradually increasing degradation; "++" = rapidly increasing degradation; "0" = stable; "NA" = no temporal or spatial data available; "?" indicates that the impact is controversial. Benthos community response is categorized as "Mortality" (moderate population reductions, many species survive) or "Mass mortality" (drastic reduction or elimination of benthos). Fisheries responses are indicated from trends in resource yields or quality.

within shallow continental shelf waters that often overlap the hypoxic zone. This is true not only for important commercial species such as shrimp (Figure 3.3) but also for benthic organisms (Figure 1.4) forming the forage base for exploited species. Although nutrients are essential to the surface production that sustains surface- and bottom-dwelling communities, including fisheries, the excess nutrients that lead to hypoxia result in the progressive degradation of the entire resource base in deeper waters (Figure 3.4). 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. The entire resource production base is strongly impacted by low oxygen conditions (Figure 3.4). Spawning grounds, migratory pathways, feeding habitats, and fishing grounds of important species are impacted by the extent and severity of hypoxic waters. Expansion of the hypoxic zone would lead to decreases in productive habitat.

Figure 3.2. Shrimp boats returning to Delacroix, Louisiana after a long day of fishing. Photograph courtesy of Louisiana Office of Tourism, Baton Rouge, Louisiana.

Trawler surveys show a decrease in or absence of shrimp and fishes in hypoxic waters. Both abundance and biomass of fishes and shrimp are significantly less where bottom water concentrations of oxygen decline below 2 mg/L (Leming and Stuntz, 1984; Renaud, 1986b). Geographic comparison of the distribution of fishing effort around the Gulf shows that the industry has shifted shrimping efforts away from hypoxic zones. Laboratory experiments show that the two most important commercial species of shrimp can detect and attempt to avoid hypoxic water (Renaud, 1986a). Because shrimp must move from inshore wetland nurseries to offshore feeding and spawning grounds, hypoxia can block their migration. Gazey et al. (1982) found that juvenile brown shrimp leaving marsh nurseries moved farther offshore when hypoxia was not present. Analyses of the distribution of the shrimp catch suggest that hypoxia interferes with shrimp migration. As early as 1983, it was noted that the shrimp catch efficiencies (measured as catch per

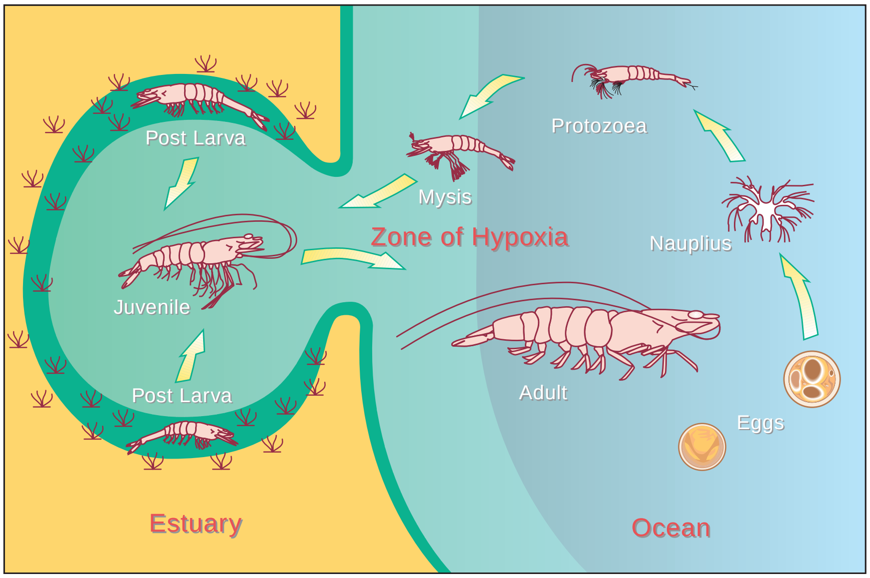

Figure 3.3. Diagram of the life cycle of Gulf of Mexico shrimp. Eggs released in the ocean develop into larvae that migrate into inshore estuaries to grow into juveniles. Juveniles migrate out to sea where they grow into adults that are of commercially harvestable size. Migration to the sea can be blocked by the hypoxic zone (blue), which is avoided by migrating juveniles.

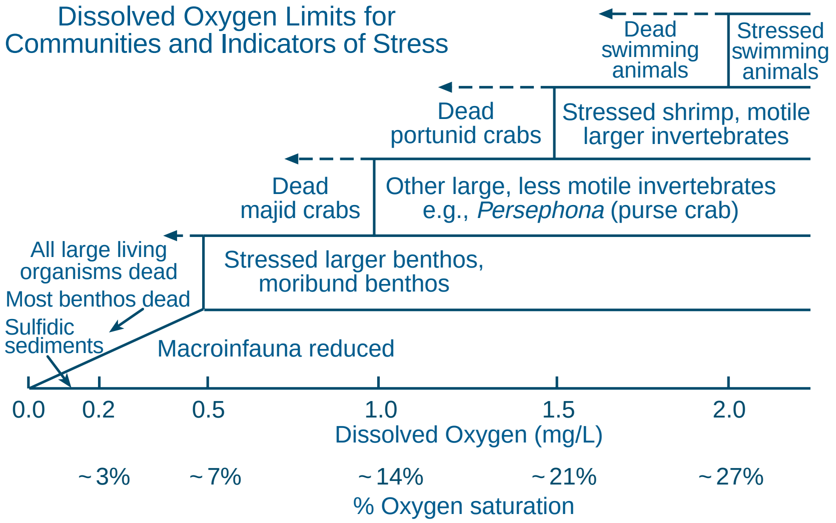

Figure 3.4. **Illustration of the systematic loss of fish and benthos as oxygen concentrations become progressively reduced. Fish (nekton) disappear below 2.0 milligrams (mg)/liter (L) dissolved oxygen, followed by eradication of other benthic organisms, as oxygen concentrations decline (figure after Rabalais and Harper, unpublished data).**

unit effort [CPUE]) declined dramatically in areas where bottom waters were hypoxic (Renaud, 1986b). In areas where bottom-water oxygen concentrations are below 2 mg/L, shrimp abundance is so low that a boat hauling a 40-foot net for 6 hours might not even catch a single shrimp (Renaud, 1986b). Such increased levels of effort required to catch shrimp or other resources must decrease net revenue to the fisheries, impacting social welfare.

Relative responses of white and brown shrimp fisheries during periods of increased hypoxia also corroborate the fisheries implications of the hypoxic zone. Because large brown shrimp require more offshore shelf habitat than white shrimp, brown shrimp should be more impacted by increased hypoxia. In fact, the brown shrimp catch in the Gulf declined from a record high in 1990 to below the historical average during years of greatly increased hypoxia (1993–1997) (Figure 3.5). White shrimp inhabit the near-shore zones, away from hypoxic waters, and have not shown as great a decline. Differences in life cycles are likely to expose brown shrimp and white shrimp to different degrees of impact at different points in their life cycles.

Other analyses (Zimmerman et al., 1997) demonstrate that localization of shrimp catch on the shelf is related to the extent of hypoxia. Where hypoxia is more frequent, shrimp catch is always low. The blocking effect on shrimp migration reveals that hypoxia impedes the movement of shrimp to offshore waters, so near-shore abundance of shrimp is high. Fishing effort and catch can both therefore be larger nearshore in Louisiana than offshore, especially when compared to other states, e.g., Texas. Because young shrimp are caught at a relatively small size in Louisiana as they exit inshore nurseries, their failure to realize the productivity from growth to larger sizes means an annual loss of several million kg of poten-

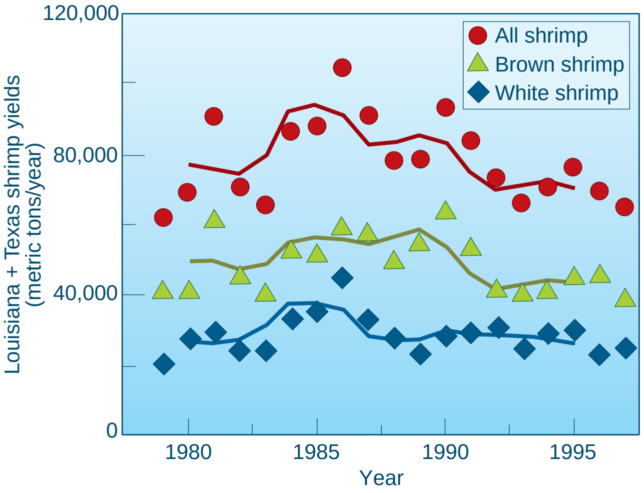

Figure 3.5. **Trends in shrimp yields recorded by the National Marine Fisheries Service for Louisiana and Texas. "All shrimp" includes species with recorded annual yields greater than 1,000 metric tons. Lines indicate 3-year moving averages. Data supplied by personal communication through the National Marine Fisheries Service Statistics and Economics Division. (http://www.st.nmfs.gov/st1/commercial/landings/index.html)**

tial shrimp yield (Nance et al., 1994). Because hypoxia blocks and eliminates access of migrating juvenile shrimp to offshore feeding grounds, lost production is probably significant over as much as 50% of the coastal shelf of Louisiana.

It is difficult to analyze the aggregate fisheries impact of degraded water quality by examining landings or dockside values. Shrimp landings in Louisiana and Texas have, however, declined about 25% since the peak yields of the mid-1980s (Figure 3.5) but the overall yield has shown no striking trend since the late 1970s. This cannot be interpreted to mean that the impact of hypoxia has been minimal. Fishing industries can adjust for poor yields by dramatically altering their effort, changing technology to improve efficiency, or fishing more distant and costly areas. This is similar to farmers altering the amount of land under cultivation or rates of fertilization in response to changes in yields or prices of commodities. Overall commodity harvests can be stabilized for finite periods, but economic efficiency is often lowered when increased effort is required. In fact, nearly constant catch and CPUE during stock collapse may be quite typical due to schooling behaviors of marine organisms and remarkable efficiencies of highly capitalized fishing fleets (Mackinson et al., 1997). So far, opportunism and adaptability in commercial fishing communities have apparently minimized the direct impact of hypoxia on total landings and the gross value of harvest. Such adaptability is typical of communities relying on naturally fluctuating resources. Changes in fishing effort and costs can decrease monetary yields and values to society. This is an especially important consideration because the overcapitalized Gulf of Mexico fisheries are facing intensified international competition. Furthermore, fisheries exploited beyond their production potential are well known for sudden economic collapse rather than gradual decreases in overall yields (Cook et al., 1997; Roughgarden and Smith, 1996).

Although declines in overall fisheries yields have not been dramatic over the period of increased hypoxia (see Figure 3.5), CPUE data from the brown shrimp and white shrimp fisheries in the Gulf are consistent with the hypothesis of increased environmental impact. Decadal average CPUEs have declined continuously since the 1960s, with the most rapid rates of decline between the 1980s and 1990s (Figure 3.6A). A similar but less steep decline has been observed in the white shrimp fishery (Figure 3.6B). CPUEs in these fisheries have declined by more than 25% since the 1960s. Decreases in CPUE are efficient and accurate estimators of the abundance and catchability of resource organisms. Although declines in the shrimp industry may be linked to changes other than hypoxia, there is no current evidence of recruitment failure; thus, the trend is consistent with the hypothesis of environmental impact (James Nance, National Marine Fisheries Service, Galveston, Texas, pers. com.).

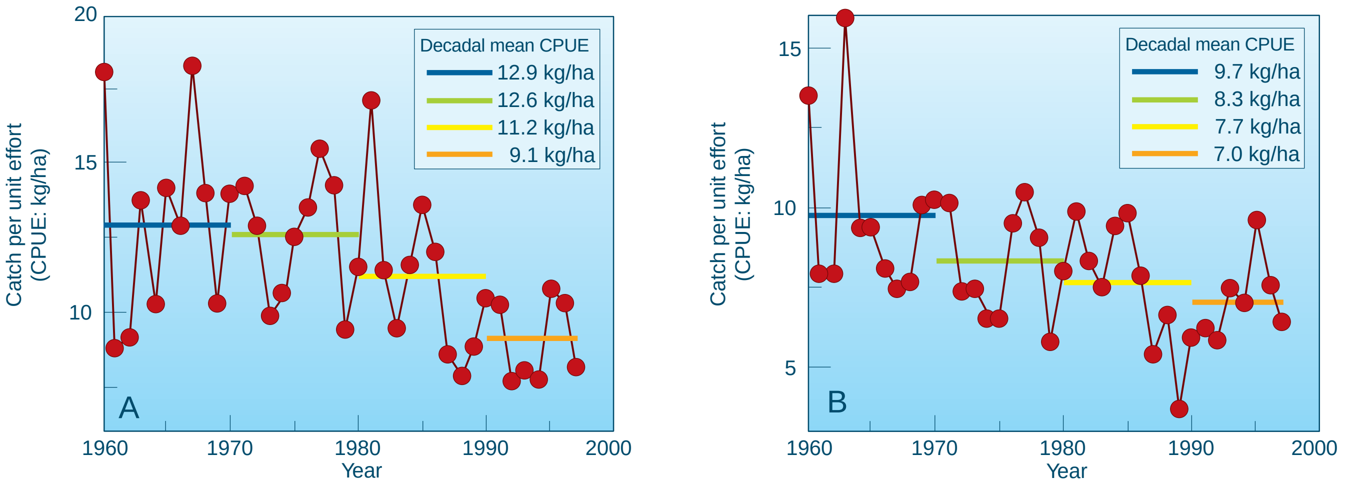

Figure 3.6. Changes in catch per unit effort (CPUE) for the (A) brown shrimp (*Penaeus aztecus*) and (B) white shrimp (*Penaeus setiferus*) fisheries of the U.S. coast of the Gulf of Mexico. This shrimp fishery is roughly centered on the region of the Gulf where hypoxia has been observed most frequently. Data represent information on CPUE specifically for these species in National Marine Fisheries Service regions 1–21 of the coastal Gulf of Mexico. Practically, however, most brown and white shrimp are caught in areas 10–21 (roughly from Mobile Bay to Padre Island). Data were supplied by James Nance of the National Marine Fisheries Service (Galveston, Texas), and are from Annual Stock Assessment Reports prepared for the Gulf of Mexico Council.

4 Probable Sources of Mississippi River Nitrogen

Introduction

Fifty-two percent of U.S. farm receipts are derived from agriculture in the Mississippi River Basin (U.S. Department of Agriculture, 1998). Agriculture has been implicated in 60% of the assessments of river water quality degradation in the United States (Council for Agricultural Science and Technology, 1992; U.S. Environmental Protection Agency, 1994), and the Mississippi River Basin covers 41% of the contiguous United States (Figure 4.1) accounting for 36% of total U.S. runoff (van der Leeden et al., 1990). Questions concerning agriculture's impact on nutrient loads are, therefore, naturally raised regarding water quality issues in the Gulf of Mexico. Farming in the Mississippi River Basin is of massive and strategic importance to the U.S. economy. Over 52% of American farms are found in the Mississippi River Basin, representing 55% of U.S. agricultural lands (including rangelands). More than 47% of the nation's rural population lives there, representing more than 33% of all U.S. farm-related jobs (U.S. Department of Agriculture, 1998). Mississippi River Basin agriculture generates gross receipts of over $98 billion annually, with more than half generated in the six top-producing states: Iowa, Nebraska, Illinois, Kansas, Arkansas, and Wisconsin.

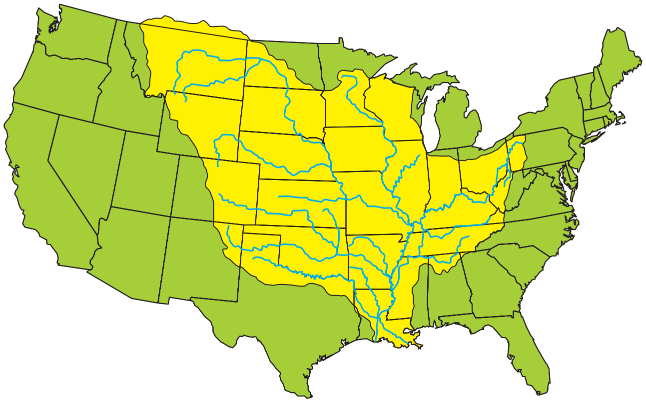

Figure 4.1. Schematic map showing the Mississippi River Basin and the major tributary rivers (after Meade, 1995).

A Diversity of Nitrogen Sources

Remediation of Gulf of Mexico eutrophication requires the identification and mitigation of major nutrient sources. At the heart of the hypoxia issue, therefore, is a determination of the relative magnitude of probable N sources in the basin. Because it is difficult to trace the sources of N supplied by the Mississippi to the Gulf of Mexico, the best identification of probable sources comes through analyzing the size of major N releases. Basing the analysis on economic, atmospheric, and census data, corrected for food and feed exports from the region (Howarth et al., 1996), the data indicate that 55% of the net N used or released to the basin is attributable to agricultural fertilizers (Terry and Kirby, 1997), 26% is from fixation by leguminous crops (Howarth et al., 1996), 2% is derived from human sewage and industry (Howarth et al., 1996), 3% comes from nonagricultural fertilizer use (compiled from the *Commercial Fertilizers Database;* Terry and Kirby, 1997), and 15% stems from anthropogenic N deposition through precipitation (Prospero et al., 1996) (Figure 4.2). Another potential source of agricultural N release is soil mineralization (Darst, pers. com., 1998; Goolsby, pers. com., 1998; Hoeft, pers. com., 1998), which may, when fully documented, substantially increase estimates of the frac-

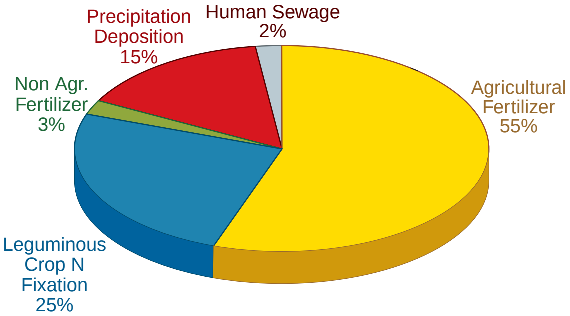

Figure 4.2. Calculated nitrogen sources of the Mississippi River Basin, corrected for exports of food and feed from the Mississippi River Basin. Calculations are based on nitrogen uses and fluxes (see text).

tion of Mississippi River N flux attributed to agricultural activities (Darst, pers. com., 1998). Data on this contribution are, however, too sparse to allow their inclusion in this report. Analyses of the relative sizes of N releases cannot, however, discern the precise allocation of N sources. For example, some agricultural N supplies atmospheric deposition and N in human sewage is supplied by N from food stuffs. Meade (1995) estimated that approximately one-fourth of the N supply to the Mississippi River Basin is derived from agricultural crop nutrients released as manure. These releases are essentially recycling of row-crop based feeds through animal manures. Others (Antweiler et al., 1995; Goolsby, 1994) have calculated that a similarly large fraction of the N delivered to the Gulf by the Mississippi River is from agricultural sources. Although many sources contribute to the problem, the sheer magnitude of N used in agriculture makes it likely that the majority of the increased N transported by the Mississippi River is of agricultural origin.

Gulf Hypoxia and Agricultural Nutrients

The sheer scale of the issue makes it difficult to imagine that agriculture many hundreds of miles up the Mississippi River could contribute to eutrophication in the Gulf of Mexico. Recent studies indicate, however, that much of the N input to huge marine ecosystems can be supplied by agricultural sources (Howarth et al., 1996; Vitousek et al., 1997a, 1997b).

Figure 4.3. Aerial photograph showing drainage patterns of farm fields in Central Iowa. The light, straight lines in the wet field are areas where tile drains have removed subsurface water. Photograph courtesy of Dr. James L. Baker, Iowa State University, Ames, Iowa.

The N lost from the Mississippi River Basin through the Mississippi River amounts to about 1.8 ∞ 10^9 kg/year (Howarth et al., 1996). If one postulates that a conservative 50% of this N results from shifts to intensive agriculture during the last century (Turner and Rabalais, 1991), this increased loading can be translated to a loss rate of an average 1,000 kg of N for each of the 1,087,500 farms in the region. This represents an N flux increase equal to about 2 to 3 kg/ha/year, averaged over all agricultural lands. Actual loss rates, of course, vary greatly among regions of the basin. Local annual N losses as drainage from agricultural lands are known to be much higher, increasing to more than 10 kg/ha/year when soil is eroded (Johnson and Baker, 1984; Siemens and Oschwald, 1978) or from 10 to 50 kg/ha/year through nitrate

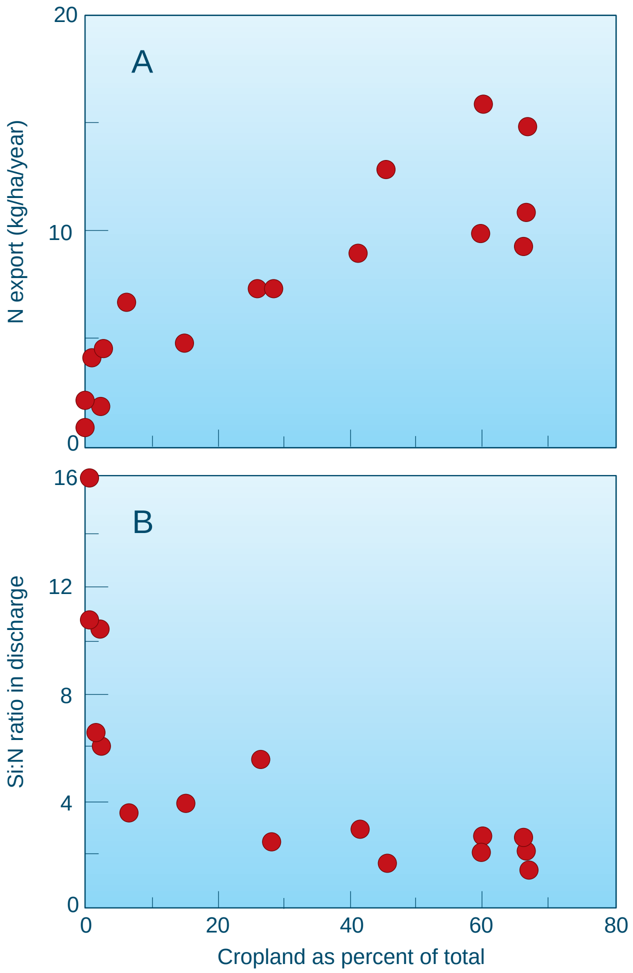

Figure 4.4. Relationship between (A) nutrient export of watersheds and (B) silica:nitrogen ratios and the fraction of each Chesapeake Bay area watershed cultivated as cropland (data from Jordan et al., 1997).

leaching with water leaving fields through drainage tiles or artificial subsurface drainage (Figure 4.3) (Baker and Johnson, 1981; Gast et al., 1978; Hatfield et al., 1995; Kanwar et al., 1988; Kladivko et al., 1991). In the Chesapeake Bay watershed, another location where agriculture contributes nutrients to the marine environment, nutrient flux has been strongly correlated with the amount of land in agricultural production (Figure 4.4A) (Jordan et al., 1997). Nitrogen inputs to these watersheds were dominated by fertilizer and manure applications and export rates were strongly correlated with anthropogenic inputs. Further, under intensive cropping in some agricultural watersheds, Si:N decreases in drainage waters (Figure 4.4B) (Jordan et al., 1997; Rabalais et al., 1996; Turner and Rabalais, 1991) can further exacerbate the problem by favoring noxious algae.

Many practices can decrease agricultural nutrient losses to receiving waters, and thus, alter downstream flux to marine environments. Although high concentrations of nitrate found in some streams are due to the total cropping system (Keeney and DeLuca, 1993), increasing N application rates raise concentrations and losses in subsurface drainage. Use of agronomic tools that can decrease N application rates, such as the late-spring soil nitrate test (Binford et al., 1992a; Magdoff et al., 1984) and assessment at crop maturity (Binford et al., 1992b) can decrease N losses, as can other improved application methodologies (Baker et al., 1997; Ressler et al., 1997). Practices such as the use of regulated buffer strips for infiltration/deposition and denitrification (conversion of nitrate to gaseous N_2 lost to the atmosphere) in natural or constructed wetlands may also help solve N flux problems (Crumpton and Baker, 1993) (see Chapter 6).

5 Nitrogen Export from Agricultural Landscapes

Methods of Transport

Nutrients are transported from land to surface and coastal waters by four carriers: air, surface runoff water, sediment, and subsurface drainage water (Figures 5.1 to 5.5). Nutrients released to the atmosphere by volatilization (e.g., loss of NH_3 gas), gaseous nutrient release (e.g., N_2O), or through wind erosion from crops and soils can be added to surface waters by wash-out with precipitation or by dry deposition/adsorption. Measurements of N transported from land to water by atmospheric transport show that it can range from 3 to 20 kg/ha/year, depending on location, source, and weather (Andraski and Bundy, 1990; Hatfield et al., 1996; Tabatabai, 1983).

Dissolved nutrients transported in surface runoff, either in solution or adsorbed to particles, originate primarily from a thin layer of soil at the land surface (termed the mixing zone in Figure 5.5). Increased rates of loss can arise through both increased concentrations of nutrients and increases in the mass of runoff water and sediment transported. Erosional nutrient losses are extreme during hydrological events such as storms and floods. Heavy, intense precipitation can have drastic impacts on surface runoff losses. Thus, factors influencing surface runoff losses include solubilization, erosion, and water flux. Another factor

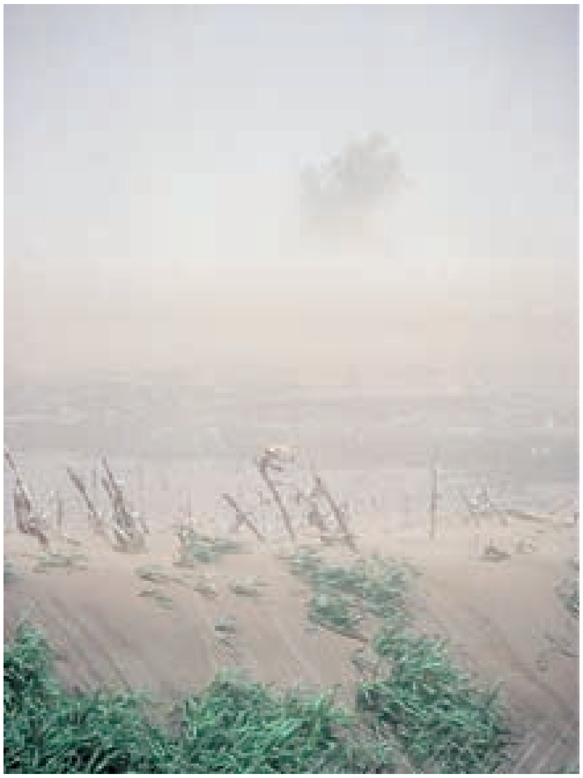

Figure 5.2. Spring windborne soil from erosion obscuring trees. Photograph by Carl Kurtz, St. Anthony, Iowa.

Figure 5.1. Spring windborne soil from erosion obscuring house. Photograph by Carl Kurtz, St. Anthony, Iowa.

Figure 5.3. Soil eroded from field by wind and deposited in a fence row. Photograph by Carl Kurtz, St. Anthony, Iowa.

Figure 5.4. Severe water erosion in farm field in Union County. Photograph by Carl Kurtz, St. Anthony, Iowa.

determining the chemical fate and transport of nutrients is the degree of soil adsorption. Therefore, factors such as the type of chemical applied as a crop nutrient amendment, the rate of application, and the method of application will affect concentrations in drainage water. Cropping, tillage, and weather (particularly the timing and intensity of rainstorms) will affect the mass of runoff water and sediment transported as well as concentrations of dissolved or adsorbed nutrients. Annual losses of N with surface runoff generally range from 1 to 50 kg/ha/year, being highly dependent on sediment losses (Baker and Laflen, 1983; Johnson and Baker, 1984; Smith et al., 1993).

Dissolved nutrients transported in subsurface drainage water (leaching loss) are dominated by nitrate-N. This is because ammonium-N and phosphate are largely adsorbed (or precipitated) from solution as they move with water through the soil to the saturated zone in subsoils, where excess water can move laterally to streams as base flow and/or artificial subsurface drainage. The most important factors in determining leaching loss are the amount of nitrate-N in the soil and the timing and amount of precipitation or irrigation that drives subsurface drainage. Therefore, N management in terms of form, rate, method, and timing of application is critical in determining concentrations and losses. Annual nitrate-N leaching losses from row-crop land with artificial subsurface drainage range from 2 to 130 kg/ha/year (Baker, 1980; Gast et al., 1978; Kladivko et al., 1991; Randall et al., 1997; Weed and Kanwar, 1996).

The field-to-stream transport of nutrients can influence loadings to streams. Nutrients can be intercepted by vegetated buffer or filter strips and wetlands. Buffer strips are more effective in decreasing transport of sediment and sediment-carried nutrients in overland flow than they are in removing dissolved nutrients (Figure 5.6). Transport of soluble nutrients can be decreased if runoff water infiltrates the buffer strip area. Buffer strips can also be effective in riparian zones where subsurface drainage water has to move laterally through subsoils, if no “short circuiting” or bypassing is provided by artificial drain tubes. Constructed, reconstructed, or natural wetlands have

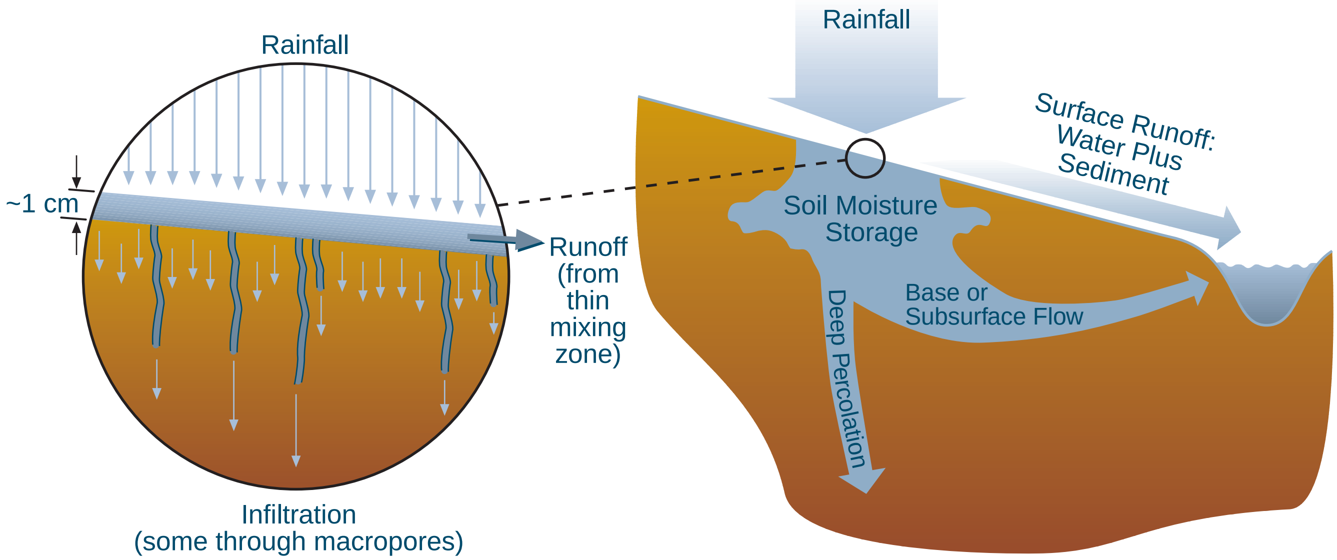

Figure 5.5. Diagram of interactions between atmosphere, soil, ground water, and surface water during the transport of nutrients to receiving waters.

Figure 5.6. A grass waterway buffer strip in corn field in central Iowa. Photograph courtesy of Dr. James L. Baker, Iowa State University, Ames, Iowa.

the potential to remove N in flow-through water and also can remove some P. Controlled drainage, where subsurface drainage is restricted during certain periods of the year, creates wet, anaerobic environments upstream of the restriction that can result in beneficial denitrification.

The relative effectiveness of management practices for decreasing agricultural N losses is compared in Table 5.1. Some management practices offer minimal (or even negative) improvements to N loss at very high cost to farmers. On the other hand, there are many highly effective N management methods that cost little to apply. Some very cost-effective examples are alterations to fertilizer application methods to decrease surface runoff and/or leaching losses of N, alterations to tillage regimes to decrease sediment-

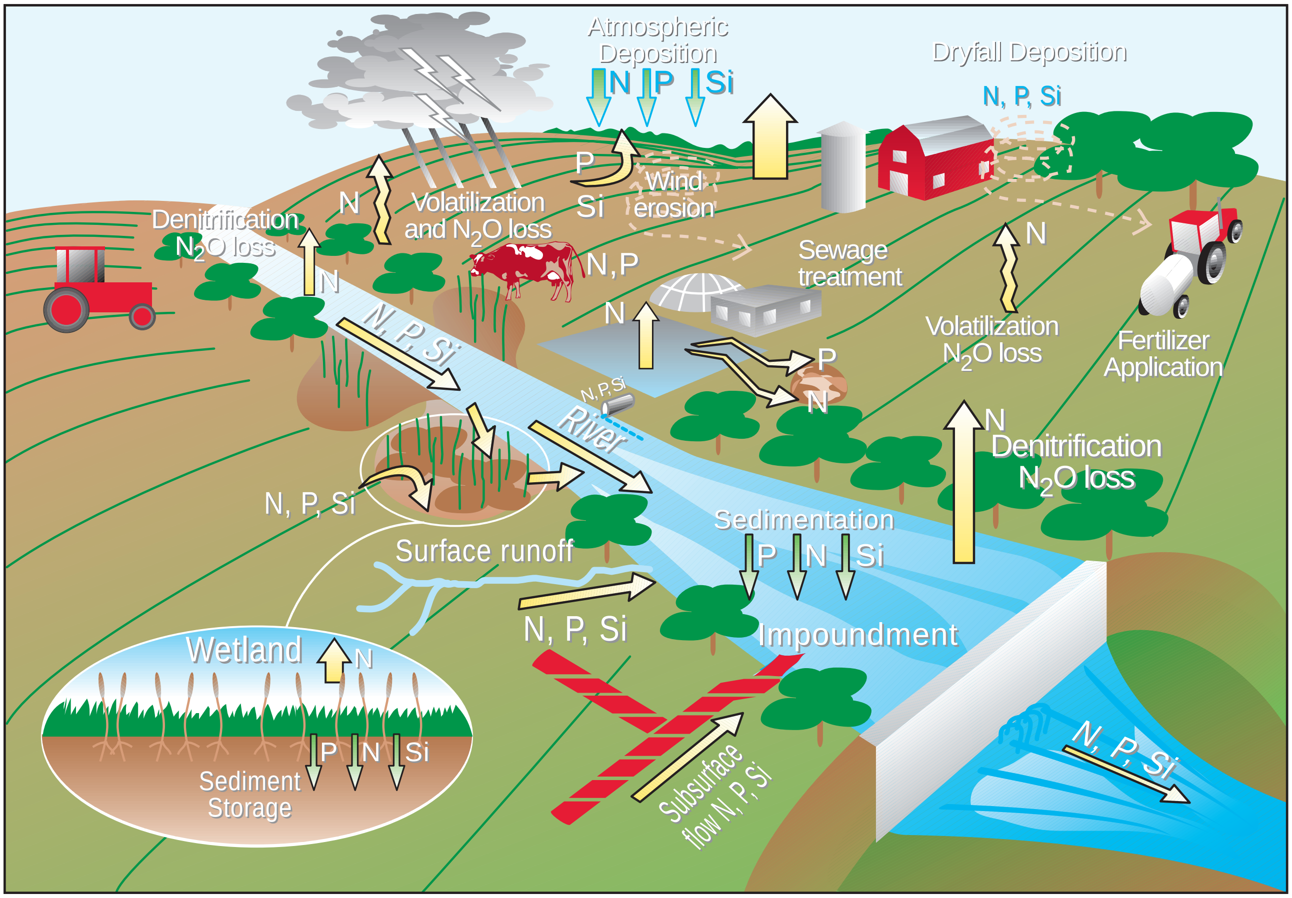

Figure 5.7. Schematic diagram of movement of three major nutrients in agricultural landscapes. Nitrogen (N), phosphorus (P), and silicon (Si) are loaded to the atmosphere by wind erosion of N, P, and Si, volitilization of NH_4, and losses of N_2O from agricultural soils. Rain and dust result in wet- and dry-depositions of these nutrients to waterways and lands. Two other major nutrient sources, runoff and subsurface flow, are illustrated at lower center. Runoff transports N, P, and Si, while subsurface flow transports primarily N and Si in many soils except those with very high soil-test P. Livestock manures can contribute substantially to both runoff and subsurface nutrient flux. Sewage and waste treatment plants discharge nutrients to surface waters but may remove some nutrients from the watershed depending on waste treatment efficiency. Nitrogen, P, and Si are trapped in wetlands, lakes, and impoundments, while bacterial denitrification can remove large amounts of N as gas to the atmosphere.

Table 5.1. Potential effects of agricultural management practices to reduce nitrogen (N) transport[a]

	N transport vehicle			
Nitrogen abatement practice	Surface runoff water	Sediment transport	Subsurface drainage	Relative net cost to agriculture
Chemical				
Alter form of applications				
NH_3/NH_4; more strongly adsorbed than NO_3–N	– to L	– to 0	L	¢
Nitrification inhibitor; maintains NH_4 form longer	– to L	– to 0	L to M	$
Alter rate of applications				
25% reduction; reduce source (e.g., 120 vs. 160 kg/ha)	L	0 to L	M to H	$$
Late-spring nitrate test; fine-tune rate vs. likely higher rate	L	0 to L	L to H	¢
Mature stalk test; assessment for possible reduction of application rate next season	L	0 to L	L to M	¢
Remote sensing; chlorophyll meter to assess N needs	L	0 to L	L to M	¢
Precision farming; variable rate vs. constant, likely resulting in lower overall rate	L	0 to L	0 to M	$
Alter method of applications				
Knife or point injection (relative to surface application)	L to H	L	0 to L	¢ to $
Soil incorporation of N with tillage	L to H	L	0 to L	¢
Localized compaction and doming	L to H	L	L to M	¢
Alter timing of applications				
Spring pre-plant; less available to be lost vs. fall	L to M	0 to L	L to H	¢
Side-dress; availability for loss/uptake affected vs. pre-plant	0 to L	0	– to L	¢
Split application; availability for loss/uptake vs. all pre-plant	0 to L	0	– to L	¢
In-field				
Change cropping system				
Rotation; corn/soybean vs. continuous corn	0 to L	– to L	L	¢
Strip intercropping (e.g., corn/soybeans/oats vs. corn/soybeans)	L	L to M	L to H	$
Cover crops; cropping between crop periods vs. none	L	L to M	L to M	$
N-fixing plants; nonsoybean legumes in rotation vs. none	L	L to M	L to M	$
Change toward perennial crops	M to H	M to H	L to M	$$
Use alternate tilling regimes				
Conservation tillage; ⊕ 30% residue cover vs. < 30%	0 to L	L to H	0	¢
No-till; no-tillage vs. < 30% residue cover	– to L	H	– to L	¢
Off-site				
Install buffer strips between fields and waterways				
Untreated area; small untreated area vs. all treated	L	L	L	$
Vegetated filter strip; vegetated untreated area vs. none (also used “in-field”)	L to M	H	0 to L	$
Use wetlands to remove nutrients and sediments				
Construction or restoration of wetlands	L	M to H	M to H	$$
Control drainage				
Restricting subsurface drainage at times	– to 0	– to 0	L to M	$

[a] “–” = slightly negative effect; “0” = no effect; “L” = low reduction (< 10%); “M” = medium reduction (10–25%); “H” = high reduction (> 25%). In the relative cost column, “¢” = low or no cost; “$” = moderate cost; “$$” = relatively high cost to agricultural producers.

bound N transport, and fine-tuning of N application rates to decrease losses through subsurface drainage (Table 5.1). Table 5.1 lists a variety of accessible N conservation techniques that are based on current technology and offer a variety of rates of economic return to farmers.

Impact of Aquatic Processing on Nutrient Flux

Once nutrients leave the land, their transport may be decreased by nutrient uptake, adsorption, denitrification, and sedimentation in streams, wetlands, lakes, impoundments, and estuarine marshes (Figure 5.7). In streams, low-flow conditions promote nitrification and denitrification (Bachmann et al., 1991), but little N is removed through uptake or sedimentation. When runoff is stored in wetlands during warm parts of the year, denitrification occurs at very rapid rates, because wetlands offer interfaces between oxygenated and anoxic waters that are rich in organic matter. The presence of aquatic plants probably stimulates rates of N removal (Seitzinger, 1990), both through gas exchange and the activity of microorganisms living on plants. The fraction of N removed by wetlands declines as loading rates increase (Downing et al., 1999; Fleischer and Stibe, 1991), so that wetlands receiving very high N flux have little impact on N transport. Sediment trapping and nutrient uptake can also remove significant quantities of N and other nutrients in wetlands, if hydraulic flushing rates and nutrient concentrations are not too high. Under poor conditions, wetlands can become N sources (Devito et al., 1989). Restored and natural wetlands are, however, one of the most effective nutrient barriers in agricultural regions.

Like wetlands, lakes and impoundments can remove N through denitrification in bottom sediments but also can retain significant amounts of nutrients through sediment storage and adsorption. Lakes and reservoirs in highly agricultural regions of the Mississippi River Basin, for example, exhibit the nutrient signatures of their watersheds, with high N concentrations in lakes with drainage basins having more than 70% crop and pasture land (Figure 5.8) (Bachmann et al., 1994). Much of this N may be retained or moved to the atmosphere by impoundments if hydraulic loading is not too rapid. For example, Windolf et al. (1996) have shown that N retention and denitrification in small, shallow reservoirs can be over 50% of the input, if the residence time of the water exceeds a few months (Figure 5.9). If flow is rapid, as is often true in landscape with enhanced drainage, lakes, reservoirs, wetlands and estuaries may remove little of the nutrient that flows into them (Nixon et al., 1996). Similar N-retention vs. water residence time relation-

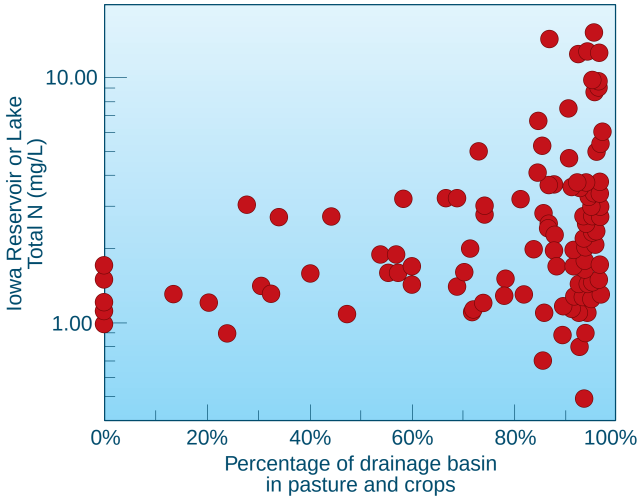

Figure 5.8. Nitrogen concentrations in lakes and reservoirs receiving runoff and drainage from agricultural watersheds in Iowa. Data are average reservoir and lake total nitrogen concentrations for most of Iowa's lakes, plotted against the fraction of the drainage basin in agricultural use (data from Bachmann et al., 1994). Lakes in Iowa are found in watersheds dominated by row-crop agriculture.

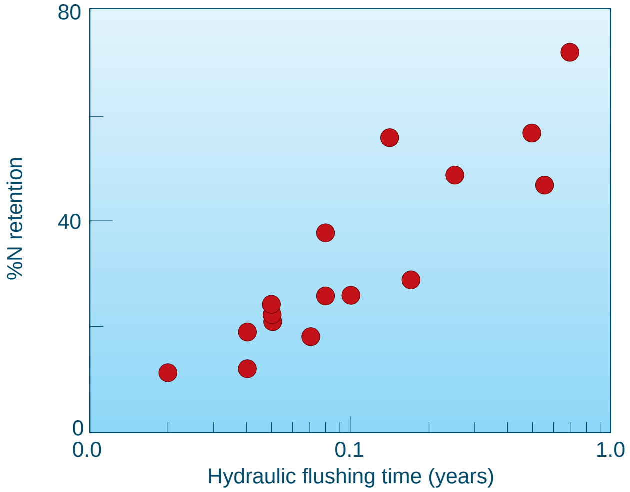

Figure 5.9. The impact of hydraulic flushing time on the fraction of nitrogen (N) flowing into lakes that is retained or lost to the atmosphere through denitrification. Data are from 16 shallow, eutrophic lakes in Denmark (Windolf et al., 1996), an agricultural region similar to many areas in the Mississippi Basin. The figure shows that lakes will remove little N in drainage basins that are flushed over very short time intervals.

ships for other lakes and rivers have been shown by Howarth (1998).

Tidal marshes and estuaries (Figure 5.10) also can be effective N sinks, unless N input rates are very high. Although coastal marine denitrification rarely exceeds 50% of input, data collected by Seitzinger (1990) suggest that high rates of N loss to the atmosphere occur in productive estuaries but are lowered in those where hydraulic flushing rates are rapid (Nixon et al., 1996) or those receiving extreme N loads (Seitzinger, 1990). Some excess N can be removed by aquatic processing in streams, rivers, wetlands, lakes, reservoirs, and estuaries, if concentrations are not extreme and water does not move through them too rapidly. Therefore, improvements due to small decreases in agricultural N losses might be amplified downstream by augmented processing of lower concentration, slower moving drainage waters.

Figure 5.10. A tidal marsh in the Chesapeake Bay in the United States. Photograph courtesy of Chesapeake Bay Program, U.S. Environmental Protection Agency, Annapolis, Maryland.

6 Costs and Benefits of Decreasing Agricultural Nutrient Export

Economic Considerations

Remediation of agricultural water quality problems may increase costs to agricultural producers but offers several economic benefits to society in general. Even though agriculture has made great strides in soil and nutrient conservation over the last two decades, the U.S. Environmental Protection Agency's National Water Quality Inventories indicate few major improvements in the quality of the nation's rivers, lakes, ponds, and estuaries since 1990. A recent National Water Quality Inventory indicates that agriculture accounts for a large portion of river water quality degradation (in river miles) and the majority of the impaired lake acreage in assessed waters (U.S. Environmental Protection Agency, 1994). Agriculture is the leading source of impairment to rivers and lakes that supply nutrients to marine ecosystems. Because agriculture is a major source of nutrients to the Gulf of Mexico, decreasing its contribution of nutrient fluxes to the Gulf will require changes in crop and livestock management practices. Such changes involve societal and private costs and benefits.

One benefit of decreasing nutrient loading would be decreased risk of impact or perception of impact on the Gulf's marine fishing industry. Other potential benefits, however, 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 foodstuffs, and improved aquatic habitat in streams, lakes, rivers, and estuaries. Societal benefits and costs of improved water quality in the United States have been evaluated on the national and regional scales (Table 6.1). Benefits are typically measured in terms of potential damage reductions. The annual costs of agricultural water quality degradation and the potential benefits of reduction can be very large, ranging from $100 million to the tens of billions of dollars.

These externalities should be compared with the costs of decreasing nutrient loads to receiving waters. At the most basic level, agricultural fertilizer's share (about 55%) of the $1.8 \infty 10^9$ kg per year of N that is added to the Mississippi River's outflow would be worth about $410 million annually if applied as an-

Table 6.1. Studies indicating potential societal benefits of U.S. agricultural water pollution remediation

Cost type	Value	Notes	Reference
Annual cost of surface water pollution in United States	$29 billion	$205–$279 per household	Carson and Mitchell (1993)
Annual pollution damage to recreational water uses	$4.6 billion	1978 dollars	Freeman (1982)
Surface water quality benefits of CRP[a] on 40-45 million acres of erodible land	$3.5–$4.5 billion	Over CRP program life	Ribaudo (1989)
Water quality damage from cropland erosion	$2.2 billion	1980 dollars	Clark et al. (1985)
Recreational fishing benefits	$300–$966 million	Annual	Russell and Vaughan (1982)
Water quality benefits of soil erosion programs	$340 million ($0.28–$1.50 ton^{-1} reduction)	1983 programs	Ribaudo (1986)
National recreational benefits of reduced agricultural soil erosion	$286 million	Since 1982	Feather and Hellerstein (1997)

[a] CRP = Conservation Reserve Program.

hydrous ammonia and liquid fertilizer (conservative cost of $0.19/lb of N) (Iowa State University Extension, 1998). Keeping lost N on the fields would represent a benefit equivalent to about 0.5% of Mississippi River Basin gross farm revenue or 2% of net cash return on individual farms' agricultural sales (U.S. Department of Agriculture, 1992).

Table 5.1 lists management practices to decrease N transport, with qualitative estimates of the magnitude of potential effects. The costs and benefits of applying these techniques vary greatly among farms. Potential costs of decreasing nutrient losses from agricultural activities include higher material, equipment, and management costs of adopting nutrient management practices (e.g., spring instead of fall fertilizer application); soil testing; plant testing; yield monitoring; precision fertilizer application; and irrigation water management. Potential costs of decreasing application rates include decreased crop yields and, for alternative cropping patterns, costs of growing less-profitable crops. Use of buffer strips or wetlands may remove land from production as well as add costs of creating these areas.

The cost to agricultural producers of practices that protect water quality is often small compared to the total costs of producing a crop. The motivation for adoption of these practices has usually been higher profit (U.S. Department of Agriculture, 1997). In fact, the principle behind best management practices (BMPs) is that they are at least as profitable as existing practices and protect or enhance water quality (Amacher and Feather, 1997). In spite of the likely profitability and effectiveness of considering legume N fixation in calculating future fertilizer applications, manure testing, soil testing, and prefertilization soil moisture testing, only 5 to 10% of producers would apply these BMPs without monetary incentives (Cooper and Keim, 1996). Many farmers are naturally risk averse and may be unwilling to adopt new practices unless they observe them being used successfully on neighboring farms (Cooper and Keim, 1996). Management practices that decrease agricultural nonpoint source pollution are often inexpensive to implement, however, and may even increase net returns to farmers (U.S. Congress, 1995).

Several demonstration projects have provided case studies of the socioeconomics of nutrient loss reductions. Studies performed under the USDA Management Systems Evaluation Area (MSEA) project yielded a variety of examples evaluating the socioeconomic factors influencing agricultural water quality in Iowa, Minnesota, Missouri, Nebraska, and Ohio (Prato, 1995). The research showed that relative costs of decreasing N losses varied greatly among specific farms. In Ohio, three cropping systems were compared: (1) continuous corn with chisel plowing and routine application of fertilizer and pesticides, (2) a "typical" system consisting of a corn-soybean rotation with routine application of fertilizer and pesticides, and (3) an agricultural system consisting of a corn-soybean-wheat/hairy vetch rotation with routine application of fertilizer and pesticides. The "typical" system provided about 50% greater economic return than the sustainable or monoculture systems. On the other hand, in Nebraska, producers in areas with high N concentrations in irrigation water could increase their economic returns and decrease ground water pollution by improving irrigation efficiency and decreasing N application rates. In Missouri, current farming systems were shown to be more profitable than those decreasing N flux but posed a higher risk of water contamination than alternative farming systems. No single farming system was dominant in terms of achieving both economic and environmental objectives. Watershed-scale analyses have shown that (1) water quality improvements substantially decreased watershed net economic returns; (2) reductions in surface water contamination by sediments and bound nutrients required changes in tillage practices, crop rotations, and idling of cropland acreage; and (3) farming systems that efficiently decreased sediment loss were less expensive and differed from those that efficiently decreased soluble nitrate concentration in agricultural drainage (Prato, 1995). Increased reliability of achieving water quality improvements generally results in decreased economic returns for producers.

Estimates of net costs and increased risks to producers of decreasing N losses from agriculture vary greatly among cropping systems, regions, and years. Empirical data on costs and risks are rare and difficult to generalize. Analyses specific to certain sites and cropping systems indicate that substantial N flux reductions may be impractical to achieve. In a recent multiyear regional modeling study involving N application in the White River Basin in central Indiana (Randhir and Lee, 1997), policies of taxing, regulating the total use, or regulating the rate of use were considered relative to economic and water quality effects. Randhir and Lee (1997) estimated that a tax of 400% of the fertilizer cost may only decrease N use by 15%, which would decrease mean income by about 7%. Nitrogen pollutants in surface and subsurface water would be decreased by about 2%. With a 40% restriction in total N use, ground water contamination was estimated to be decreased 30%, with mean income decreased about 2%. Restricting the N use per unit area with decreases of 6, 30, and 54% from baseline rates resulted in shifts in cropping systems while water quality improved substantially. At the 6% restriction, mean income was not severely affected, but average rates of risk to farm income increased substantially. Although specific to a given location, additional analyses would allow a clearer picture of the costs and benefits of reductions in fertilizer application.

No individual study has documented the benefits and costs of decreasing nutrient loads to the Gulf of Mexico. Several national and regional studies have shown that the social benefits of decreasing agricultural nonpoint nutrient flux (Table 6.1) exceed the private costs by a substantial margin (Prato, 1995). A comprehensive evaluation of the benefits and costs of decreasing nutrient flux to the Gulf of Mexico would require a determination of (1) required reductions in nutrient loads to assure productivity of commercial and recreational fisheries and (2) specific costs and benefits of attaining those reductions. Such an assessment should evaluate all sources of private and social benefits and costs, then determine the economic efficiency of decreasing nutrient loads to levels that would relieve the Gulf's hypoxia.

The Social Environment of the Hypoxia Issue

Agricultural nutrient flux may be controlled by cost-effective measures, but such broad shifts in practice can be limited by farmers' knowledge of these measures and their motivation to apply them. The social context of rural Mississippi River Basin agriculture is therefore of great importance.

In 1998, a quantitative telephone survey was used to assess rural Mississippi River Basin residents' attitudes about environmental and watershed issues, their knowledge of hypoxia, and their attitudes about several potential remedial measures (Downing and Padgitt, 1998). The survey was modeled after the "Health of the Planet Survey" (Dunlap et al., 1993) and polled 503 rural Mississippi River Basin residents in Arkansas, Illinois, Indiana, Iowa, Kansas, Louisiana, Minnesota, Missouri, Montana, Nebraska, and South Dakota

Only about 11% of the rural Mississippi River Basin residents surveyed were aware of the hypoxia problem. Although rural residents of Louisiana were four times more aware of the issue than those in other states, there was no general relationship between distance from the Gulf and knowledge of hypoxia. When asked how important they believe it is to protect the Gulf from hypoxia, 67% responded that it is "very important" and only 2% felt that it was "not important at all." More than 80% of those polled felt that it is "very believable" or "somewhat believable" that agricultural nutrients cause a hypoxic zone in the Gulf, and 95% felt that it is "important" to protect the Gulf from agricultural nutrients if they do, in fact, impact it.

Table 6.2 shows some of rural Americans' evaluations of the effectiveness of several possible measures to solve the Gulf hypoxia problem. Those polled favored research to find the "smoking gun," education and extension to help solve the problem, and incentives to decrease nutrient losses. Citizens recognized the need for information on nutrients and hypoxia. Some doubted its link to agriculture but thought it should be solved if it can be shown to be caused by agricultural nutrients. Many residents support the need for research, education, extension, and incentive programs as effective means of solving it.

Table 6.2. Results of a telephone survey of 503 rural residents of the Mississippi River Basin showing the relative perceived effectiveness of potential steps to address Gulf of Mexico hypoxia. Data were obtained during February and March of 1998 by random telephone interviews of adults in randomly selected rural households (Downing and Padgitt, 1998)

Possible steps to address hypoxia	Judged potentially "effective" (%)
Education to teach farmers ways of keeping nutrients from going to Gulf of Mexico	88
Research documenting nutrient sources	87
Reward farmers who use methods that keep nutrients out of rivers	86
Limit farm fertilizer use	67
Install treatment plants to remove nutrients from rivers	56
Help fishing communities find jobs that don't rely on fish in the Gulf	49
Tax fertilizers to support Gulf	38
Tax food to support Gulf restoration	29

7 The Future of Hypoxia in the Gulf of Mexico

Oxygen deficiency (hypoxia) may be the most widespread, anthropogenically induced, deleterious effect in estuarine and marine environments worldwide. It causes mortality of bottom-dwelling fauna, including important fishery species. Over the last 20 to 30 years, the number of coastal areas with seasonal hypoxia in their bottom water has been increasing rapidly. The main cause is eutrophication through the delivery of excess nutrients to marine systems. No other environmental parameter of such ecological importance to estuarine and coastal marine ecosystems has changed so drastically, in such a short period of time, as dissolved oxygen. While hypoxic environments have existed through geologic time, their occurrence in estuarine and coastal areas is rapidly increasing and accelerated by human activities. The importance of oxygen as a factor for maintaining populations of fisheries-related species cannot be overemphasized.

Increasing nutrient loads in many places in the world have led to large-scale loss of marine resources. Recovery of marine systems is possible but often quite slow. In locations where nutrient influx reductions have been attempted, e.g., the Baltic Sea, the Kattegat, the Black Sea, and many Scandinavian fjords and Mediterranean bays, short-term recovery has been slow. Slow recovery may be due to nutrient and carbon burial in marine sediments that continues to deplete oxygen long after deposition (Rabalais et al., 1998). Lack of shrinkage of Gulf of Mexico hypoxia in the few years after the 1993 flood suggests that recovery from peak periods of hypoxia can take several years after decreases in riverine nutrient flux.

Several success stories illustrate improvement of smaller estuarine and coastal ecosystems in response to nutrient abatement in the watershed or abatement of direct discharges to the system. Management and intervention to decrease nutrient loads, particularly P, in Tampa Bay, Florida, have led to success in ecosystem restoration, including improved water clarity, decreased instances and biomass of cyanobacterial blooms, expanded submerged aquatic vegetation (seagrass beds), increased catch of seagrass-dependent fishes (e.g., the valuable speckled sea trout), and improved dissolved oxygen conditions in bottom waters (Johansson and Lewis, 1992). Retention reservoirs and weirs in upstream channels of Bayou Texar near Pensacola, Florida were coupled with improved sewage treatment for an improvement in water quality. Fish kills were almost completely eliminated, accompanied by a 90% reduction in phytoplankton primary production, a virtual elimination of algal blooms, and re-establishment of public use (Moshiri et al., 1981). Decreasing nutrient flux by half has led to a decrease in the frequency of toxic red tides in the Seto Inland Sea of Japan (Cherfas, 1990). Sewage treatment improvements resulted in better water quality in Kaneohe Bay, Hawaii (Smith, 1981). These studies illuminate the possibility of recovery following a decrease in nutrient loading of the Gulf of Mexico.

Decreases in agricultural nutrient flux can be accomplished with current technology (Table 5.1). Water quality-motivated alteration of cropping strategies would likely increase costs to producers and consumers but would yield very large societal benefits (Table 6.1). The magnitude of restoration needed to affect changes in much larger coastal systems with much larger watersheds—such as the Chesapeake Bay, Long Island Sound, the Baltic Sea, and the northern Gulf of Mexico—seems daunting, especially given the immense economic importance of the agricultural activities supplying the nutrients.

The Chesapeake Bay has been the focus of both intensive research on cultural eutrophication, including hypoxia, and extensive efforts to decrease nutrient inputs that cause it (Boesch et al., 1999; Malone et al., 1993). Strong public and political support has brought progress in decreasing nutrient inputs to the bay, particularly from point sources (Figure 7.1). Concentrations of N and/or P in stream flow have been decreased in several major rivers. Although there have been no statistically significant declines in nutrient concentrations in the open waters of the Bay, nutrient concentrations have declined in several tidal rivers where demonstrable load reductions have been achieved. The extent of hypoxia has not yet decreased, but some modest decreases in algal biomass have occurred, along with some encouraging signs of recovery of submerged aquatic vegetation.

The lessons to be learned from the Chesapeake Bay and other areas of the world are (1) degradation of marine water quality and increased oxygen stress have occurred over decades; (2) multilevel and multi-institutional support is required to institute nutrient management; (3) because biological restoration is slow to respond, results of controls will be slow to materialize; (4) natural climate variability can mask restoration due to fluctuations in freshwater discharge and the nutrients it carries; (5) ecosystem restoration following nutrient abatement is achievable; and (6) benefits of restoration accrue to multiple facets of society. The Gulf of Mexico can recover from eutrophication. Success will be slow in coming but a broad spectrum of society can benefit from decreased nutrient fluxes in the Mississippi River Basin.

Recommendations

The magnitude of human activities is now so great that watersheds have shrunken to the point that activities high in the Corn Belt can impact life in the Gulf of Mexico. It is important to recognize that the small changes made by many can combine to make large changes, which can be detected and felt in very different environments many hundreds of miles distant. With this knowledge, we make these seven general recommendations.

Figure 7.1. Storm water runoff flowing into Chesapeake Bay in the United States. Photograph courtesy of Chesapeake Bay Program, U.S. Environmental Protection Agency, Annapolis, Maryland.

1. Efforts should be undertaken and infrastructure created to control, retain, and monitor nutrients leaving agricultural and other key lands throughout the Mississippi River Basin.
2. Research should be supported to create, enhance, and distribute information on cost-effective nutrient management methods for use by agriculture, with an eye toward promoting more nutrient-effective food production.
3. All levels of society should set and achieve specific goals of nutrient flux reduction that are tied to downstream water quality improvement; all decreases in nutrient flux (not just from agriculture) will help local *and* distant quality of life.
4. All approaches to nutrient flux reduction should seek cost-effective solutions that enhance water quality, the strategic agricultural society of the rural Mississippi River Basin, and the unique coastal society of the Gulf of Mexico.
5. The cost-effectiveness of nutrient flux solutions should be judged on the basis of both societal and private costs and benefits.
6. Policies should be created and implemented that permit key segments of society to favor long-term, broad strategies that enhance life and environment in the Mississippi River Basin and its receiving waters.
7. Efforts should be undertaken and continued in the Gulf to monitor changes in hypoxia and its potential causes, as well as to conduct comprehensive analyses of the impacts of marine eutrophication on society and environment.

Appendix A: Synonyms and Acronyms

BMPs	best management practices	lb	pound
BSi	biogenic silicon	m	meter
CPUE	catch per unit effort	mg	milligram
ft	foot	mi	mile
h	hour	MSEA	Management Systems Evaluation Area
ha	hectare	N	nitrogen
kg	kilogram	P	phosphorus
km	kilometer	sec	second
L	liter	Si	silicon

Appendix B: Glossary

Agro-ecosystem. Ecosystem under agricultural management.

Algae. A group of aquatic plants, many of which are microscopic, that are among the principal primary producers in freshwater and marine ecosystems. Examples of algae are phytoplankton, green and brown "pond scum," and large marine seaweeds.

Allochthonous. Consisting of or formed from transported material originally accumulated elsewhere.

Amendment. Substance, such as manure, compost, and fertilizer that is added to soil to make it more productive.

Anaerobic. Without oxygen.

Anhydrous ammonia. NH_3-N, often applied as nitrogen fertilizer.

Anoxia. The absence of dissolved oxygen.

Anthropogenic. Conditions generated by human activities.

Atmospheric deposition. Addition of nutrient material dissolved in precipitation and the addition of nutrients carried by dry particulates in the air, e.g., dust.

Atmospheric transport. Lateral movement of nutrients or other materials with air masses.

Benthic organisms. Organisms living in or on the bottom of aquatic environments, e.g., polychaetes, clams, snails.

Benthos. Organisms living on the bottom of aquatic ecosystems.

Best management practices (BMPs). Cropping systems designed to reduce environmental impacts at no- or low-cost to farmers.

Bloom. An explosive increase in the population of phytoplankton. Algae blooms are often associated with eutrophic conditions and are frequently composed of noxious algae species.

Buffer strip. Untreated and usually a vegetated piece of land often within or at the edge of fields above receiving waters that permits the infiltration of water and the removal of eroded particles from agricultural runoff.

Burial. Sedimentation and sequestering of organic matter at the bottom of the sea.

Chlorophyll. Pigments found in plant cells that are active in harnessing energy during photosynthesis. Chlorophyll concentrations of phytoplankton in the water column are often measured as surrogates of phytoplankton biomass or productivity.

Collapse (of a fishery). The catastrophic decline in fishing yield or commercial viability of a fishery.

Conservation tillage. Methods of tillage that maintain a cover of crop residues on the soil surface and either reduce the amount of tilling (reduced tillage or minimal tillage) or eliminate it altogether (no-till).

Continental shelf. The shallow part of seas near the continents where the bottom shelves gradually slope from shore to a depth of about 200 m.

Cover crops. Special crops planted to keep soil surface from eroding and possibly help retain nutrients.

Crop residue. Plant material remaining after harvesting, including leaves, stalks, roots.

Crop yield. Quality and quantity of a crop harvested.

Cropland. Total area on which field crops, fruits, vegetables, nursery products, and sod are grown.

Cropping system. The combination of tillage and agricultural practices used to grow and manage a given crop.

Cultural eutrophication. Eutrophication due to human impacts.

Cyanobacteria. One group of sometimes noxious phytoplankton, i.e., bluegreen algae.

Decomposition. The breakdown of organic matter by bacteria and other heterotrophic organisms. Decomposition of large amounts of organic matter depletes dissolved oxygen concentrations.

Deep-sea. The part of marine environments that is beyond and below the continental shelf.

Demersal organisms. Organisms associated with the bottom of aquatic environments, but capable of moving away from it, e.g., blue crabs, shrimp, red drum.

Denitrification. The conversion of soluble nitrate nitrogen to gaseous N_2 and its release to the atmosphere.

Diatom. A major phytoplankton group characterized by cells enclosed in silicon (glass) frustules, or shells.

Discharge. The amount or mass of water or material released from rivers to receiving waters.

Dockside value. The amount of money that commercial fishermen or women receive for their catch when they off-load at dockside.

Dryfall deposition. The deposition of nutrients from the atmosphere as dust and other dry particles.

Effluent. Liquid waste discharged by industries and other producers into sewage systems and waterways.

Erosion. Removal of soil particles through the action of water, wind, or tillage.

Estuarine. Pertaining to estuaries.

Estuary. A semi-enclosed body of water that is connected with the open sea and within which sea water is diluted with freshwater derived from land drainage. Also applied to the lower reaches of rivers where seawater intrudes and mixes with freshwater as well as to bays, inlets, gulfs, and sounds into which rivers empty.

Eutrophication . An increase in organic production of an ecosystem, usually associated with very high rates of nutrient supply.

Existence value . The value that people place on the existence of a healthy ecosystem.

Externalities . Costs or benefits that do not accrue to the economic unit that creates them.

Fertilization. Application of plant nutrients to the soil in the form of commercial fertilizers, animal manure, and other amendments.

Flushing . The rate at which water is passed through a system.

Flux. Another term for movement of water or material from one place to another.

Foraminifera . Marine protozoans that produce calcium carbonate in their cell walls that are deposited in sediments that can be analyzed to provide measures of past oxygen conditions.

Hydraulic flushing . The rate at which water is passed through a system.

Hydraulic loading . Rate at which water is input to a system.

Hydrogen sulfide. A toxic chemical that diffuses into the water as the oxygen levels above aquatic sediments become very low.

Hydrological . Pertaining to the flow of masses of water.

Hypoxia . Very low dissolved oxygen concentrations, generally 2 milligrams of dissolved oxygen per liter of water.

Impoundment . A reservoir where water is held behind a control structure.

Intercropping . Alternating tilled crops in narrow strips across a long slope.

Jubilee . The crowding of fish, shrimp, and crabs onto a beach from deeper hypoxic waters pushed onshore because of wind shifts. A jubilee is sometimes followed by a fish kill, if the oxygen level is severely low, prolonged, or situated such that no escape is possible for the organisms.

Irrigation . Artificial watering of land using water channels, pipes, or sprayers.

Knife injection . Injection of fertilizer below the soil surface.

Landings . The amount or monetary value of marine resources that are brought to land.

Late-spring nitrate test . Testing soil to fine-tune nitrogen amendment rates.

Leaching . The transport of nutrients and other materials down through the soil profile through the action of water.

Legume credits . Nitrogen amendment reductions permitted by growing nitrogen fixing plants in previous years.

Leguminous crops . Agricultural crops that have structures that can take up nitrogen directly from the gaseous nitrogen (N_2) in the air.

Levees . Raised dikes along the sides of rivers.

Life cycle . The behavioral and biological details of the cycle of the natural history of a species as it goes from birth to adulthood, reproduction and death.

Loading . The net amount of input to a system.

Marine . Relating to the sea.

Mineralization (soil) . Inorganic nutrient release from the organic components of soils through biological and chemical means.

N_2O. Nitrous oxide, a chemical material that is lost to the atmosphere during denitrification.

Nitrate . Water-soluble inorganic nitrogen of the form NO_3.

Nitrification . The conversion of dissolved ammonium-nitrogen to nitrate-nitrogen.

Nitrite . Water-soluble inorganic nitrogen of the form NO_2.

Nonpoint pollution . A diffuse source of chemical and/or nutrient inputs not attributable to any single discharge, e.g., agricultural runoff, urban runoff, atmospheric deposition.

No-till . Tillage practice involving direct seeding, which does not disturb the soil surface.

Noxious algae . The many forms of algae that grow under particular conditions and form a nuisance of some kind, including some toxic risk to humans or marine animals.

Nutrient retention . Holding onto nutrients by plants, land, water bodies, or water courses.

Nutrients . Chemical elements (especially nitrogen, phosphorus, and silicon) that are required for the growth of phytoplankton and other plants and animals.

Organic matter . Plant and animal residues.

Orthophosphate . Water-soluble inorganic phosphorus of the form PO_4.

Overland flow . Water flowing over the soil surface as runoff.

Phytoplankton . Minute plant life, e.g., algae, that usually passively drift in a water body.

Plume (river plume) . The area where river water mixes with seawater at or near the mouth of a river.

Point injection . Injection of fertilizer below the soil surface.

Point source. Refers to a nutrient source that is localized and usually large in magnitude, e.g., a sewage outfall, an industrial discharge.

Precision farming . Detailed, spatially explicit methods of measuring soil characteristics, fertilizer needs, and resulting crop yields.

Productivity . The conversion of light energy and carbon dioxide into living organic material by phytoplankton and other plants.

Pycnocline. The region of the water column characterized by the strongest vertical rate of change in density. Pycnoclines can arise from vertical gradients in temperature, salinity, or both.

Remote sensing . Aerial or satellite photography to make measurements of land or water characteristics. For example, remote sensing can be used to measure crop chlorophyll as a means of adjusting fertilizer application rates or determining differences among marine water masses.

Residence time . The average time that water stays in a system. If the residence time is short, the flushing rate is rapid.

Respiration . The consumption of oxygen during energy utilization by cells and organisms.

Retention reservoir . Impoundment designed to retain sediment and nutrients.

Revetment . A stone or concrete facing to retain an embankment and decrease erosion.

Riparian zone . The land along the edges of natural water courses, e.g., streams, rivers, or lakes.

Rotation . Annual alteration of crops with different nutrient requirements, e.g., corn and soybeans planted in alternate years as opposed to continuously replanting only corn.

Runoff. Portion of the total precipitation that flows overland and enters surface streams rather than infiltrating the soil.

Seagrass beds . Submersed aquatic vegetation (vascular plants) that are important areas for the production of marine animals.

Sediment (marine and freshwater) . Materials of marine, freshwater, or terrestrial origin deposited on the bottom by the slow sinking of particles. Usually composed of detrital material and inorganic soils.

Sediment (watershed) . Soil particles.

Shelf . *See* continental shelf.

Side-dressing . Fertilizer application in a band next to rows of emergent plants.

Solubilization . Dissolving nutrients in water.

Split application . Fertilizer amendment generally both before and after crop emergence.

Stratification . The separation of water masses into layers isolated by pycnoclines. Stratification keeps layers of water from mixing and hinders the transport of dissolved gases and chemicals from one layer to another.

Strip-cropping . Alternating tilled crops in narrow strips often across a long slope.

Subsoils . Layers of soil found below the original level of plowing between the topsoil and parent material.

Subsurface drainage . Water leaving the land either naturally through ground water or through perforated drainage tiles underlying soils.

Sulfidic sediments . Marine or freshwater sediments that are anoxic and therefore generate toxic hydrogen sulfide.

Surface water . Water occurring on the surface of the land, such as streams, rivers, ponds, lakes, and oceans.

Thermal stratification . A condition where water divides into layers based on temperature differences, i.e., a pycnocline is formed due to water density differences associated with water masses of different temperatures.

Tile drains . Perforated and unperforated pipes used to drain excess water away from agricultural lands.

Tillage . Mechanical preparation of the soil for seeding, for fallow, or for weed control.

Trawler . A type of fishing boat that drags a large net behind it to capture marine organisms swimming in the water or living near the surface of the bottom.

Volatilization . Direct movement of material to the atmosphere.

Wash-out . The removal of gaseous or suspended nutrients from the air by transport to earth with precipitation.

Water column . A term applied to the vertical profile of water from the surface to the water-sediment interface.

Watershed. The portion of a drainage basin that contributes runoff and ground water to a given surface water body or watercourse.

Waterways . Drainage channels in agricultural fields.

Weir . A small dam to raise water levels and improve retention of nutrients and sediments.

Wetland . A permanent or seasonal shallow body of standing water that is often vegetated with emergent and/or submergent vascular plants.

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