HYPOXIA IN THE GULF OF MEXICO

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INTRODUCTION

There is increasing concern in many areas around the world that an oversupply of nutrients from multiple sources is having pervasive ecological effects on shallow coastal and estuarine areas. While a variety of changes may result in the increased accumulation of organic matter in a marine system (= eutrophication, as defined by Nixon [1995]), the most common single factor is an increase in the amount of nitrogen and phosphorus marine waters receive. With an increase in the world population, a focusing of that populace in coastal regions and agricultural expansion in river basins, eutrophication is becoming a major environmental problem in coastal waters throughout the world. Humans have altered the global cycles of nitrogen and phosphorus over large regions and increased the mobility and availability of these nutrients to marine ecosystems (Peierls *et al.* 1991; Howarth *et al.* 1996; Vitousek *et al.* 1997; Caraco and Cole 1999). These human-controlled inputs are the result of human populations and their activities, particularly the application of nitrogen and phosphorus fertilizers, nitrogen fixation by leguminous crops, and atmospheric deposition of oxidized nitrogen from fossil-fuel combustion. Changes in the relative proportions of these nutrients, as well as silicate, may exacerbate eutrophication, favor noxious algal blooms and aggravate conditions of oxygen depletion (Officer and Ryther 1980; Smayda 1990; Conley *et al.* 1993; Turner *et al.* 1998).

Excess nutrients lead to degraded water quality through increased phytoplankton or filamentous algal growth. Increasing nutrient loads are the cause of some noxious or harmful algal blooms (HABs), including toxic forms. Secondary effects include increased turbidity or oxygen-depleted waters (= hypoxia) and, eventually, loss of habitat with consequences to marine biodiversity. Over the last two decades it has become increasingly apparent that the effects of eutrophication, including oxygen depletion, are not minor and localized, but have large-scale implications and are spreading rapidly (Diaz and Rosenberg 1995; Nixon 1995).

Water with less than 2 mg L^{-1} dissolved oxygen is said to be hypoxic. Hypoxia occurs naturally in many parts of the world's marine environments, such as fjords, deep basins, open ocean oxygen minimum zones, and oxygen minimum zones associated with upwelling systems, such as the one off the Yucatan shelf (Kamykowski and Zentara 1990). Hypoxic and anoxic (no oxygen) waters have existed throughout geologic time, but their occurrence in shallow coastal and estuarine areas appears to be increasing (Diaz and Rosenberg 1995). It is these areas of the Gulf of Mexico upon which this chapter focuses.

DISTRIBUTION OF HYPOXIA IN NORTHERN GULF OF MEXICO ESTUARIES

Not all coastal systems with elevated nutrient loads are conducive to the process of eutrophication or development of hypoxia. Many rivers deliver large quantities of fresh water laden with nutrients and organic carbon, but zones of nutrient-enhanced productivity and/or bottom-water hypoxia/anoxia do not develop. The processes of increased phytoplankton biomass, carbon accumulation, and oxygen depletion are more likely to occur in estuarine or coastal systems that are characterized by longer water residence times and stratified water columns, either salinity- or temperature-controlled, or both. The amount of suspended sediment delivered to a coastal system also factors into whether enhanced production will result from high nutrient inputs.

The volume of freshwater discharge, exclusive of the nutrient load, can influence residence time, stratification, turbidity and nutrient dilution. High flow years of the Mississippi River result in intensified stratification on the adjacent continental shelf, higher chlorophyll biomass and more widespread bottom-water hypoxia (Rabalais *et al.* 1998). In other estuaries, such as the Hudson River estuary, higher discharge years result in lower residence time, increased turbidity, less stratification, lower primary production and less eutrophication (Howarth *et al.* 2000). The same higher Hudson River discharge onto the continental shelf of the New York bight, however, would have similar results as Mississippi River outflow with increased stratification, chlorophyll biomass and bottom-water hypoxia (Swanson and Sindermann 1979; Whitledge 1985).

Among estuaries of the United States, features of those in the Gulf of Mexico make them more conducive to the development of hypoxia than those on the east or west coasts (Fig. 26.1) (Turner 2001). The range of population within the watershed, which is a good predictor of nutrient loads, is similar between Gulf estuaries and others. The average water depth of Gulf of Mexico estuaries is less than other U.S. estuaries — a feature that would enhance wind-driven mixing and reduce the likelihood of stratification and hypoxia. The related smaller tidal range and higher sediment accumulation rates, however, would increase the residence time of water and increase the accumulation of organic matter. Also, the subtropical climate of the Gulf of Mexico estuaries compared to others in the U.S. increases the rates of biological processes including photosynthesis and respiration.

HYPOXIA ADJACENT TO THE MISSISSIPPI AND ATCHAFALAYA RIVERS

The largest zone of oxygen-depleted coastal waters in the United States, and the entire western Atlantic Ocean, is found in the northern Gulf of Mexico on the Louisiana/Texas continental shelf, an area that is influenced by the freshwater discharge and nutrient load of the Mississippi River system (Fig. 26.2) (Rabalais and Turner 2001). The mid-summer bottom areal extent of hypoxic waters (≤ 2 mg L^{-1} O_2) in 1985-1992 averaged 8000 to 9000 km^2 but increased to up to 16,000 to 20,000 km^2 in 1993-2002 (Figs. 26.3 and 26.4). Hypoxic waters are most prevalent from late spring through late summer, and hypoxia is more widespread and persistent in some years than in others. Hypoxic waters are distributed from shallow depths near shore (4 to 5 m) to as deep as 60 m but more typically between 5 and 30 m. Hypoxia occurs mostly in the lower water column but encompasses as much as the lower half to two-thirds of the water column. Hypoxia begins to develop below the pycnocline in mid to late spring, then expands and intensifies through late summer until tropical storm activity or a series of cold fronts disrupts the stratification and reaerates the water column. The development of eutrophication and hypoxia is related to riverine nutrient loading, principally as nitrate, that increased in the last half of the 20th century. Nutrient-enriched waters stimulate *in situ* production of organic material which, when it sinks to the bottom layer, consumes oxygen faster than it can be replaced by vertical mixing through the stratified water column. Changes in the coastal ecosystem are directly linked with changes within the watershed and nutrient loading. Increases in algal production and worsening of hypoxia paralleled increases in flux of nutrients.

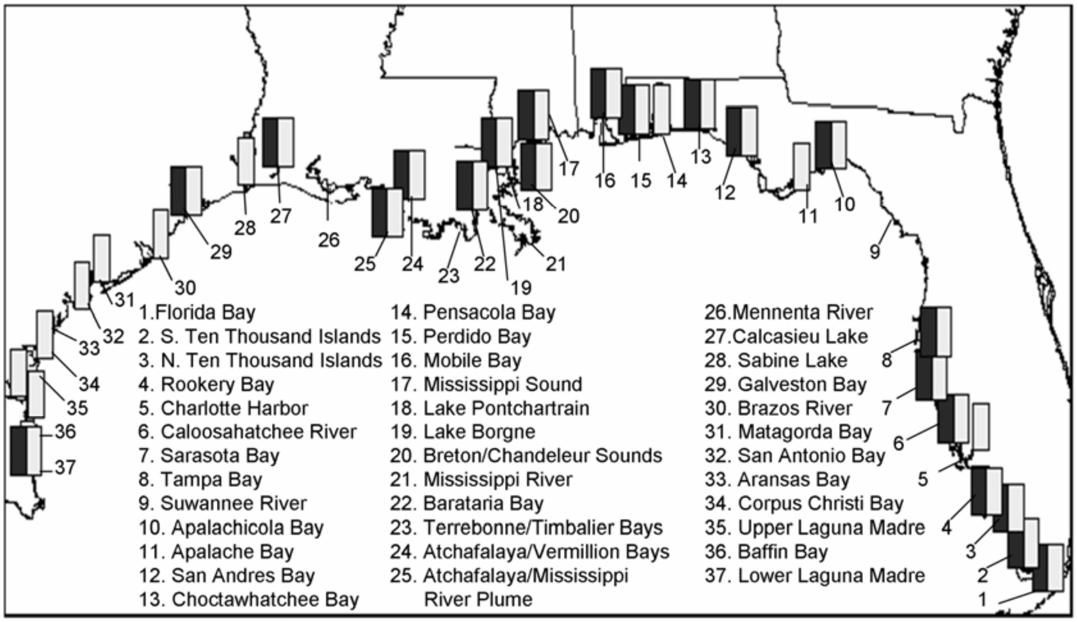

Fig. 26.1. Location of estuaries in the northern Gulf of Mexico that experience hypoxia (yellow**)** or anoxia (red) at some time during the year (from Bricker *et al.* 1997).

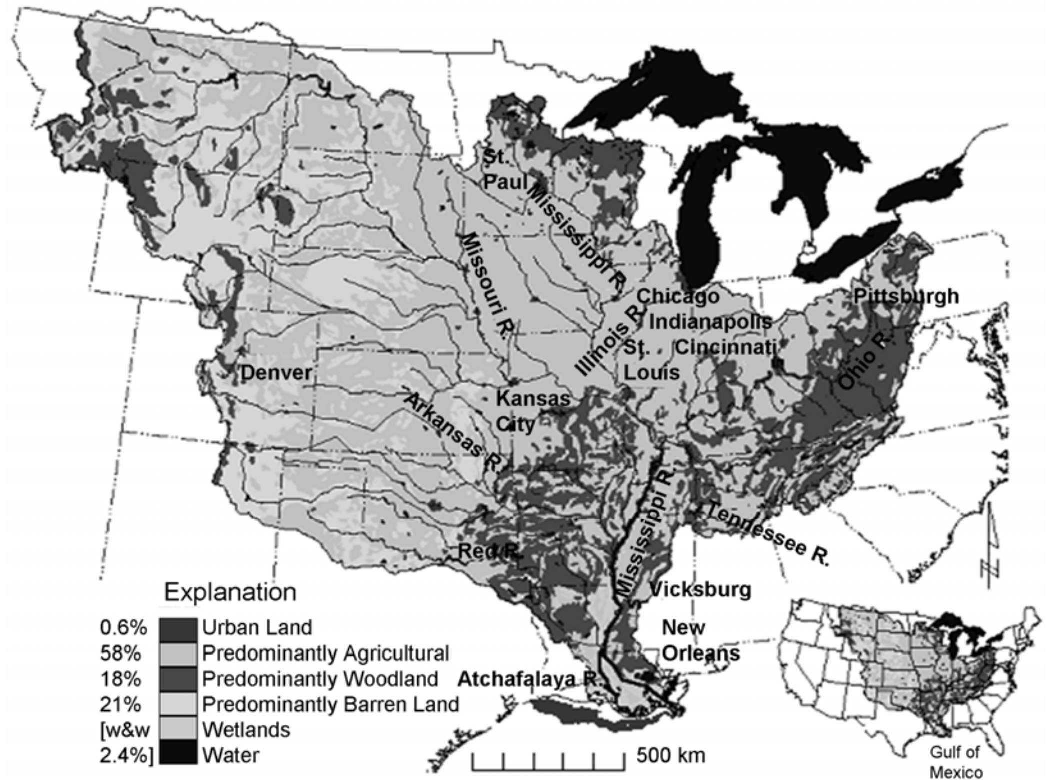

Fig. 26.2. Drainage and land use in the Mississippi River watershed (modified from Goolsby *et al*. 1999) with the 2001 area of hypoxia superimposed (data source: N. Rabalais).

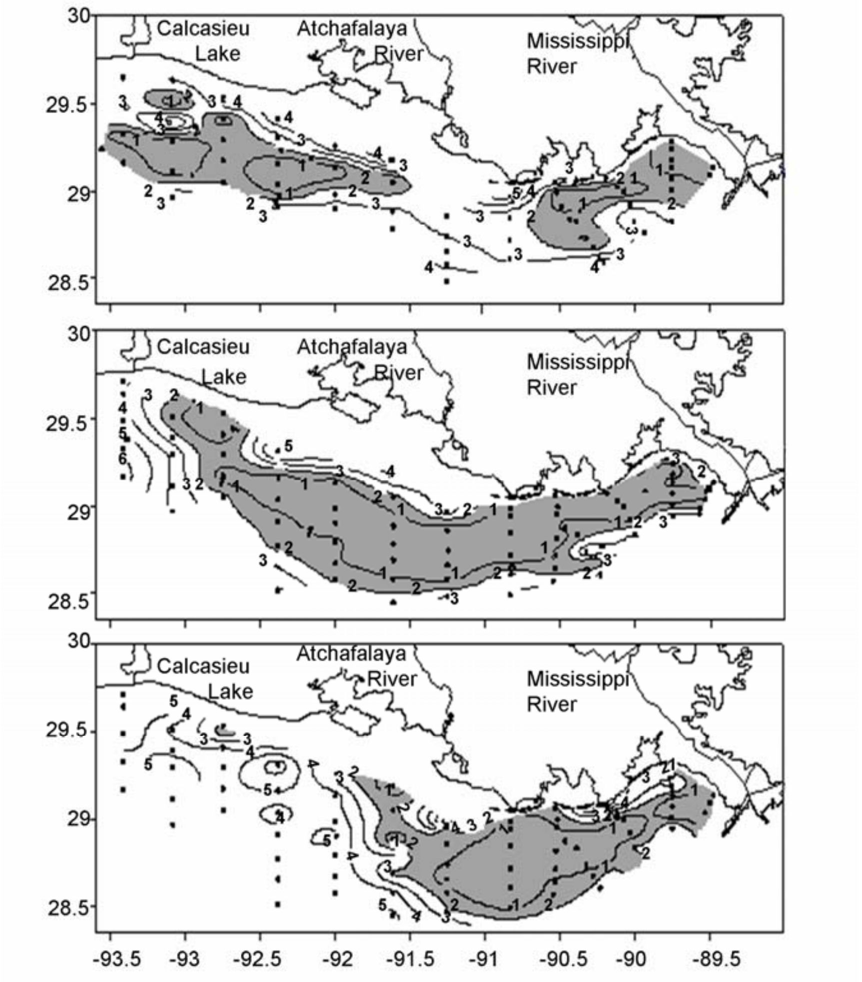

Fig. 26.3. Bottom-water oxygen contours for mid-summer cruises in 1986, 1993 and 1998. The area of dissolved oxygen less than 2 mg L^{-1} is indicated by shading (data source: N. Rabalais).

The Mississippi River system discharges an average 580 km^3 of fresh water per year to the northern Gulf of Mexico through two main distributaries — the main birdfoot delta southeast of the city of New Orleans, Louisiana and the Atchafalaya River delta 200 km to the west that carries about one-third of the flow (Fig. 26.1) (Meade 1995). The fresh water, sediments, and dissolved and particulate materials are carried predominantly westward along the Louisiana/Texas inner to mid continental shelf especially during peak spring discharge. Current reversals toward the east in summer during low discharge help to retain the fresh water and its constituents on the continental shelf. Although the area of the discharge's influence is an open continental shelf, the magnitude of flow, annual current regime and average 75-day residence time for fresh water result in an unbounded estuary stratified for much of the year due primarily to salinity differences with intensification of stratification in summer from surface thermal

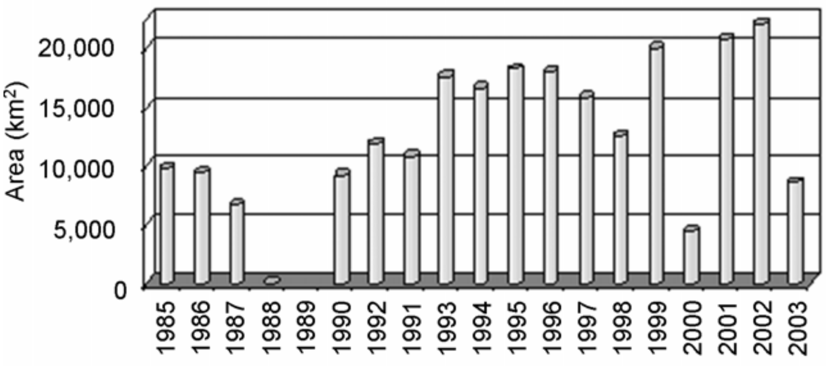

Fig. 26.4. Estimated areal extent of bottom-water hypoxia ($\leq$ 2 mg L^{-1}) for mid-summer cruises in 1985-2003 (updated from Rabalais *et al.* 1999, Rabalais and Turner 2001). Years 1988 and 2000 were drought years (summer and spring, respectively) in the Mississippi River watershed. A series of tropical storms disrupted stratification and hypoxia in 2003. (Data source: N. Rabalais)

warming. The outflow of the Mississippi and Atchafalaya Rivers is so immense that it dwarfs all other inputs of fresh water. The Mississippi and Atchafalaya rivers are the primary riverine sources of fresh water to the Louisiana continental shelf (Dinnel and Wiseman 1986) and to the Gulf of Mexico (80: of freshwater inflow from U.S. rivers to the Gulf [Dunn 1996]).

Dunn (1996) calculated the nutrient inflows from 37 U.S. streams discharging into the Gulf of Mexico for 1972-1993. With respect to the 37 streams draining into the Gulf of Mexico (Texas – Florida), the combined flows of the Mississippi and Atchafalaya Rivers account for 91% of the estimated total nitrogen load. If only streams between Galveston Bay (Texas) and the Mississippi River Delta are considered, i.e., those most likely to influence the zone of hypoxia, the combined flows of the Mississippi and Atchafalaya rivers account for 96% of the annual freshwater discharge and 98.5% of the total nitrogen load. Similar calculations for annual total phosphorus load are 88% of the total 37 streams and 98% of the streams between Galveston Bay and the Mississippi River Delta for the relative contribution of the Mississippi and Atchafalaya rivers.

The Mississippi River watershed encompasses 41% of the lower 48 United States, draining an area of 3.2 million km^2. Land use in the watershed that supports 27% of the United States' population (about 70 million people) is predominantly agriculture (Fig. 26.2) (Goolsby *et al.* 1999), the conversion of which began in the early 1800s as settlers migrated west across the North American continent (Turner and Rabalais 2003). By the 1850s the population center was in the midwestern states as the land brought under cultivation rose and developed into what is now known as the nation's "bread basket." Within the Mississippi River basin, 56% of the wetlands have been lost to agriculture, navigation, reservoirs and leveeing. Artificial subsurface drainage in much of the croplands expedites the transport of nitrate from the soil to surface waters. This management practice coupled with the increase in fertilizer applications can only increase the flux of nitrate from agricultural fields to the receiving waters of the Mississippi River watershed. The Mississippi River has also been modified for navigation and flood control with levees extending along the lower river from Cairo, Illinois to the Gulf of Mexico.

In addition to landscape changes, anthropogenic inputs of nitrogen and phosphorus have increased from agriculture, point sources, and atmospheric deposition. The annual discharge of the Mississippi River system contributes sediment yields of 210 x 10^6 t, 1.6 x 10^6 t nitrogen, of which 0.95 x 10^6 t is nitrate and 0.58 x 10^6 t is organic nitrogen, 0.1 x 10^6 t phosphorus and 2.1 x 10^6 t silica (Goolsby *et al.* 1999). The estimate of current river nitrogen export from the Mississippi River watershed over "pristine" river (pre-agricultural and pre-industrial condition) nitrogen export is a 2.5- to 7.4-fold increase (Howarth *et al.* 1996). Agricultural activities are the largest contributor of nitrate to streams and, of all the major nitrogen inputs to croplands, only fertilizer and legumes have increased since the 1950s (Fig. 26.5). The average concentration and flux of nitrogen (per unit volume discharge) increased from the 1950s to 1980s, especially in the spring; this is consistent with fertilizer use in the watershed (Turner and Rabalais 1991).

Because the amount of fresh water delivered (affects stratification) and nitrogen loading (affects primary production) influence the distribution and dynamics of hypoxia, it is important to understand the interannual variability in discharge as it affects seasonal biological processes. Using two different approaches, Donner *et al.* (2002) and Justić *et al.* (2003) agreed that 20 to 25 % of the increased nitrate flux between the mid-1960s to the mid-1990s is attributable to greater runoff and river discharge, with the rest due to increased nitrogen loading on the landscape. With nitrate concentrations in the lower Mississippi River stabilized near 100 μM since the early 1990s, climate-driven changes in discharge now clearly influence the seasonal formation of hypoxia.

Evidence from long-term data sets and the sedimentary record demonstrate that indicators of increased productivity in marine ecosystems, i.e., eutrophication of the continental shelf waters and subsequent worsening of oxygen stress in the bottom waters, are highly correlated with historic increases in riverine dissolved inorganic nitrogen concentrations and loads over the last 50 years (Rabalais *et al.* 2002). Evidence comes in long-term changes in Secchi disk depth and diatom productivity, increased accumulation of diatom remains and marine-origin carbon in sediments, and increases for surrogates for worsening oxygen conditions in the sediments—glauconite abundance, benthic foraminiferans, and ostracods. The sediment data suggest that hypoxia was not a feature of the continental shelf before 1900 and that hypoxia *may* have existed at some level before the 1940–1950 time period, but that it has worsened since then. Recent models of size and intensity of hypoxia related to nitrate flux from the Mississippi River (Justić *et al.* 2002; Scavia *et al.* 2003; Turner *et al.* 2003) indicate that hypoxia as a widespread phenomenon was not likely on the Louisiana shelf before the early 1970s.

The hypoxic zone of the northern Gulf of Mexico falls within an area of important commercial and recreational fisheries. As the depletion of oxygen progresses, the ability of organisms to reside, or even survive, either at the bottom or within the water column is affected (Rabalais and Turner 2001). When oxygen levels fall below critical values, those organisms capable of swimming (*e.g.*, demersal fish, portunid crabs and shrimp) evacuate the area. The stress on less motile fauna varies, but they also experience stress or die as oxygen concentrations fall to zero. Important fishery resources are variably affected by direct mortality, forced migration, reduction in suitable habitat, increased susceptibility to predation, changes in food resources and disruption of life cycles. The effects of eutrophication, including hypoxia, are well known for some systems and include the loss of commercially important fisheries (*e.g.*, Baltic and Black Seas). The multi-level impacts of increased nutrient inputs and worsening hypoxia are not known for many components of productivity in the Gulf of Mexico, including pelagic and benthic, primary and secondary, food web linkages, and ultimately fisheries yield.

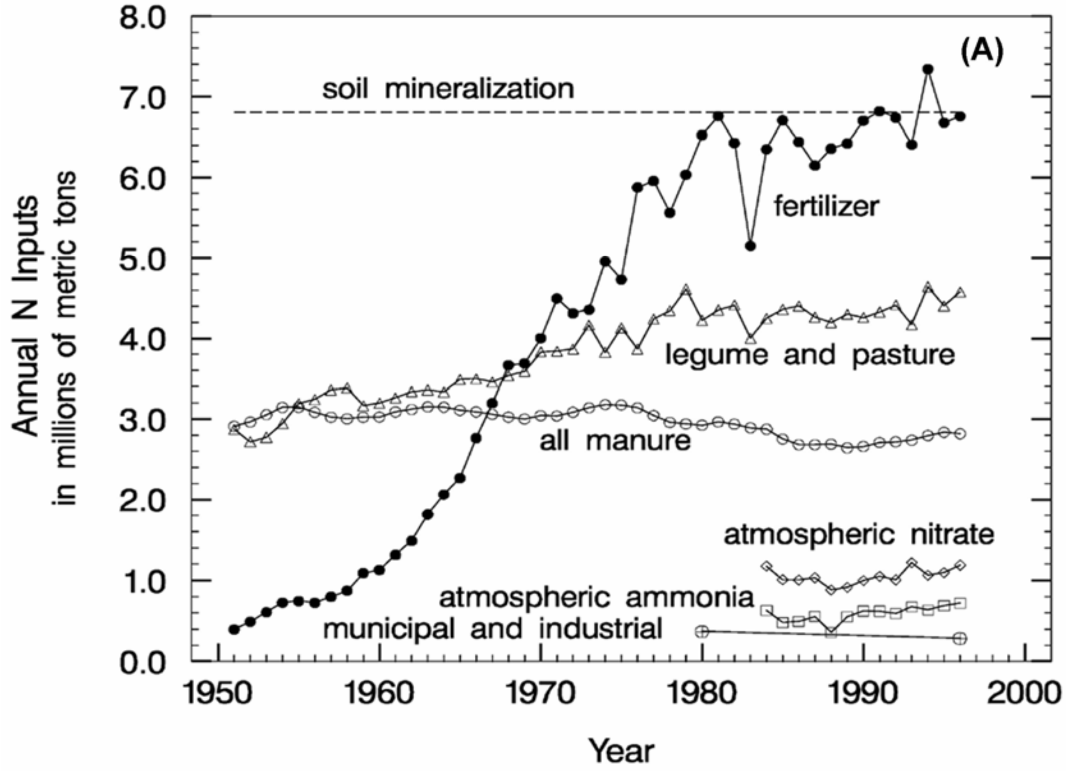

Fig. 26.5. Annual nitrogen inputs from major sources in the Mississippi River Basin, 1951-1996 (from Goolsby *et al.* 1999).

Consider, however, 20,000 km^2 of a usually productive seabed where trawlable fish and shrimp fisheries do not exist for extended periods in the summer. While there have been no catastrophic losses in fisheries resources in the northern Gulf of Mexico and, in fact, increases in the abundance of some pelagic components, the potential impacts of worsening hypoxia on ecologically and commercially important species and altered ecological processes warrant attention.

LIKELIHOOD OF HYPOXIA IN THE SOUTHERN GULF OF MEXICO

The only site listed by Diaz and Rosenberg (1995, and subsequent updates) for Mexico is Laguna Nichupté, Cancun, which experiences diel hypoxia throughout the year due to excess organic loading and an overgrowth of algae (Elva G. Escobar-Briones, Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autónoma de México, D.F., México, pers. comm.). Other lagoons, especially those with extensive seagrass beds such as Laguna Madre de Tamaulipas, Laguna de Tamiahua and Laguna de Términos, likely experience hypoxia on a diel basis similar to other seagrass habitats as nighttime respiration rates exceed oxygen resupply from the atmosphere. This process, however, is natural in these habitats. The potential harm from eutrophication processes for seagrass beds is the effect of excess nutrients causing the growth of filamentous algae on the blades or shading effects of excess phytoplankton biomass in the water column. Both types of excess algal growth lead to the decline of sea grasses and the essential habitat they provide for other organisms, including nursery habitat for important commercial species.

Any confined harbor or restricted-flow estuary that receives treated or untreated sewage, agricultural runoff, or deposition of nitrogen from burning of fossil fuels (power plants, vehicles) is susceptible to the formation of hypoxia. The flux of nutrients and oxygen-demanding materials are proportional to the population in an estuarine watershed. Although there are no substantiating data, likely candidates would be Veracruz and Havana, as well as those that receive freshwater inflow, including the harbors of Tuxpan with the Río Tuxpan, Tampico with the Río Panuco and Coatzacoalcos with the Río Coatzacoalcos.

Where larger rivers enter the southern Gulf of Mexico, such as the Río Coatzacoalcos in the southwestern Bay of Campeche and the Grijalva–Usumacinta and Champoton rivers on the southeastern Bay of Campeche, coastal hypoxia could develop **if** there were stratification and accumulation of phytoplankton biomass. There is a continuous transition of terrigenous sediments to carbonate sediments on the Campeche shelf along these outflows from west to east. The terrigenous sediments that dominate the shelf adjacent to the Coatzacoalcos indicate some level of sediment accumulation that would result from the almost permanent cyclonic gyre that may also be conducive to the formation of hypoxia, given sufficient nutrient loading and enhanced primary productivity. To date, there has been no documentation of hypoxia in this area; however, the lack of infaunal metazoans off the Río Coatzacoalcos delta in summer and higher organic matter content in sediments indicate that hypoxia likely occurs there (Elva G. Escobar-Briones, Instituto de Ciencias del Mar y Limnologia, UNAM, D.F., México, pers. comm.). On the Campeche shelf adjacent to the Grijalva-Usumacinta rivers there are more terrigenous sediments inshore where hypoxia may develop as opposed to carbonate sediments offshore where the longshore current promotes mixing.

CONCLUSION

Most marine systems respond to an increase in nutrient inputs with an increase in primary production. If surface productivity is enhanced in prey species that are preferred by the community of zooplankton grazers, then there will likely be increased productivity in pelagic and demersal populations that depend on either the living cells or the detrital material that sinks to the seabed, respectively. There are thresholds, however, where the load of nutrients to a marine system and the carbon produced exceeds the capacity for assimilation, and water quality degradation occurs with detrimental effects on components of the ecosystem and on ecosystem functioning. Prolonged oxygen depletion can cause mass mortalities in aquatic life, disrupt aquatic communities, cause declines in biological diversity, impact the capacity of aquatic systems to support biological populations, and disrupt the natural cycling of elements.

Comparisons of ecosystems along a gradient of increasing nutrient enrichment and eutrophication or changes of a specific ecosystem over time through a gradient towards increasing eutrophication, provide information on how nutrient enrichment affects coastal communities. A summary by Caddy (1993) of semi-enclosed seas demonstrates a continuum of fishery yield in response to increasing eutrophication. In waters with low nutrients, the fishery yield is low. As the quantity of nutrients increases, the fishery yield increases. As the ecosystem becomes increasingly eutrophied, there is a drop in fishery yield but the decreases are variable. The benthos are the first resources to be reduced by increasing frequency of seasonal hypoxia and eventually anoxia followed by bottom-feeding fishes. The loss of a planktivorous fishery follows as eutrophication increases, eventually with a change in the zooplankton community composition. Where the current northern Gulf of Mexico fisheries lie along the continuum of increasing eutrophication is not known.

As more and more of the United States' and world's coastal waters become hypoxic or as hypoxia increases in severity where it exists now — a trajectory proposed by many researchers and resource managers — what will happen to the habitats, the resource base, the food webs, and ultimately resources of importance for human consumption? The Gulf of Mexico is not unique among the world's coastal waters, or immune to negative impacts, as hypoxia worsens. While there have been no catastrophic losses in fisheries resources in the northern Gulf of Mexico and, in fact, increases in the abundance of some components, the potential impacts of worsening hypoxic conditions are likely, given the experience in other systems (*e.g.*, Baltic and Black Seas) where there was a precipitous decline of ecologically and commercially important species.

Reducing excess nutrient delivery to estuarine and marine waters for the improvement of coastal water quality, including the alleviation of hypoxia, requires individual, societal and political will. Proposed solutions are often controversial and have societal and economic costs in a narrow and short-term sense. Yet, multiple, cost-effective methods of reducing nutrient use and delivery can be integrated into a management plan that results in improved habitat and water quality, both within the watershed and the receiving waters (National Research Council 2000). Successful plans with successful implementation and often successful results span geopolitical boundaries, for example the Chesapeake Bay Agreement, the Comprehensive Conservation and Management Plans developed under the U.S. National Estuary Program for many of the nation's estuaries, a Long Island Sound agreement, the efforts of Denmark, Holland and Sweden, and international cooperation among the nations fringing the Baltic Sea as part of the Helsinki Commission (Boesch and Brinsfield 2000). These efforts are usually more successful in reducing point sources of nitrogen and phosphorus than with the multiple nonpoint sources of high solubility and growing atmospheric inputs of nitrogen. There are demonstrated successes of reduced nutrients, such as coral recovery in Kaneohe Bay, Hawaii and the improved water clarity and recovery of seagrass beds in Tampa and Sarasota Bays, Florida (Smith 1981; Johansson and Lewis 1992; Alderson *et al.* 1995). The growing decline of coastal water quality and the proven successes of reducing nutrients are sufficient reasons for continued and expanded efforts to reduce nutrient over-enrichment and the detrimental effects of hypoxia.

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