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Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River

NANCY N. RABALAIS, R. EUGENE TURNER, AND DONALD SCAVIA

Coastal eutrophication is a major, global environmental problem that tracks increases in population and the concentration of those increases in coastal regions, increased agricultural production in adjacent river basins, and increasing food and energy consumption. Society has altered global nitrogen and phosphorus cycles and increased the availability of these two nutrients to marine ecosystems through generation of wastewater, application of fertilizers, nitrogen fixation by leguminous crops, and atmospheric deposition of oxidized nitrogen from fossil-fuel combustion (Peierls et al. 1991, Howarth et al. 1996).

These increased nutrient loads often result in the degradation of water quality as more and more phytoplankton or macroalgae grow, including some noxious and toxic algal species. Additional effects, including increased turbidity, oxygen-depleted (i.e., hypoxic) waters, and loss of habitat, tend to decrease marine biodiversity and alter ecosystem structure and functioning. Changes in the relative proportions of nitrogen, phosphorus, and silicon can exacerbate eutrophication, favor harmful algal blooms, aggravate oxygen depletion, and alter marine food webs (Officer and Ryther 1980, Conley et al. 1993, Justic et al. 1995, Turner et al. 1998a). Over the last half of the 20th century, it became increasingly apparent that these symptoms of eutrophication were not minor and localized, but rather had large-scale ecosystem implications and were spreading rapidly (Diaz and Rosenberg 1995, Nixon 1995, Bricker et al. 1999, NRC 2000, Cloern 2001).

The linked Mississippi and Atchafalaya Rivers and northern Gulf of Mexico system is a prime example of the worldwide trend of increasing riverborne nutrients and resulting diminution of coastal water quality. The Mississippi River system ranks among the world's top 10 in length, freshwater discharge, and sediment delivery, and it drains 41% of the contiguous United States (Milliman and Meade 1983).

Editor's note: This article was derived from a plenary address at the March 2001 AIBS annual meeting.

> NUTRIENT POLICY DEVELOPMENT FOR THE MISSISSIPPI RIVER WATERSHED REFLECTS THE ACCUMULATED SCIENTIFIC EVIDENCE THAT THE INCREASE IN NITROGEN LOADING IS THE PRIMARY FACTOR IN THE WORSENING OF HYPOXIA IN THE NORTHERN GULF OF MEXICO

A third of the flow from the Mississippi River mainstem is diverted into the Atchafalaya River, where it joins the Red River for eventual delivery through a delta 210 kilometers west of the main Mississippi River birdfoot delta. Prevailing currents from east to west move most of the freshwater, suspended sediments, and dissolved and particulate nutrients onto the Louisiana and Texas continental shelf. At the terminus of this massive river system is the largest zone of oxygen-depleted coastal waters in the western Atlantic Ocean (Figure 1).

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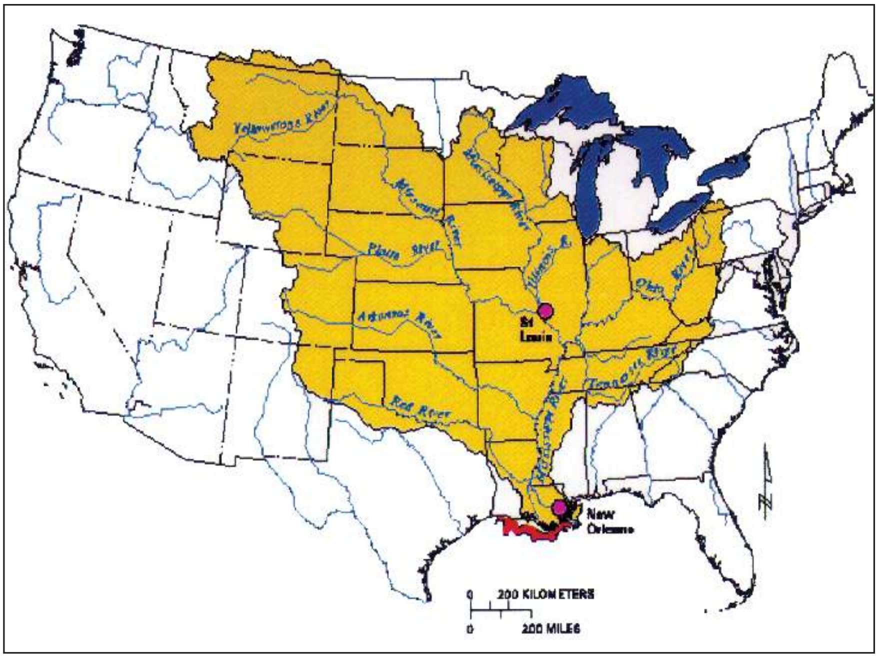

Figure 1. Mississippi River drainage basin and major tributaries, and general location of the 1999 midsummer hypoxic zone. From Goolsby (2000); used with permission of the author.

A clearer understanding of the causes and consequences of Gulf of Mexico hypoxia has emerged over the past two decades through numerous peer-reviewed publications and reports, whose highlights are summarized in this article. That increased knowledge has been instrumental in the garnering of political, societal, and institutional support in recent years for nutrient management strategies to improve water quality in the northern Gulf of Mexico and the Mississippi River basin. *The Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001), which was recently agreed to by government agencies at the federal, state, and tribal levels and delivered to Congress, prompted us to review the development of knowledge on hypoxia and how it has influenced public policy.

Our emphasis in this article is on showing how scientific understanding of the linked riverine–oceanic system grew along with science-based resource management strategy. The lessons learned from the interactions of science and policy in the context of an issue of such massive scale will, we hope, be applicable to other regions and to other large-scale ecological issues.

The what, when, and where of hypoxia: 1970–2001

At about 20,000 km^2, the Gulf of Mexico's midsummer bottom-water hypoxic zone is currently the second largest in the world in area. Only the hypoxic zone of the Baltic basins (at approximately 70,000 km^2) has more area. The bottom-water area of the Gulf covered by hypoxia in midsummer 2001 reached 20,700 km^2, a zone larger than New Jersey but not quite the size of Massachusetts. The areal extent of the Gulf hypoxic zone is twice that of the total surface area of the Chesapeake Bay, and its volume is an order of magnitude greater than the Chesapeake's hypoxic water mass (Rabalais 1998). By comparison, the extent of hypoxia on the northwestern shelf of the Black Sea peaked in the 1980s at 20,000 km^2, making that zone the second-largest coastal hypoxic water mass at that time. The Black Sea coastal hypoxic area has shrunk at the same time fertilizer use in the Danube River watershed has decreased substantially (since 1990), with subsequent decreased loadings of both nitrogen and phosphorus.

The operational definition of hypoxia in the northern Gulf of Mexico is the presence of levels of oxygen of no more than 2 milligrams per liter, because shrimp and demersal fish are not caught by trawlers at oxygen levels below that value (Leming and Stuntz 1984, Renaud 1986). Gulf surface waters are typically saturated (oxygen levels greater than 8 mg per L) at summertime temperatures and salinities. Hypoxic waters occur naturally in many marine environments, such as fjords, deep basins, deep-ocean oxygen minimum zones, and oxygen minimum zones associated with western boundary upwelling systems. Hypoxic and anoxic (i.e., devoid of oxygen) waters have existed throughout geologic time, but the occurrence in shallow coastal and estuarine areas appears to be increasing (Diaz and Rosenberg 1995) and now affects more than half of US estuaries (Bricker et al. 1999). Hypoxic conditions in estuaries and coastal waters occur predominantly where water temperature and salinity differences between surface and bottom-water layers lead to water column stratification, where water residence time is long, and where organic loading drives high respiration rates in the water column beneath the pycnocline and in the sediments.

Mapping Gulf hypoxia: 1970–1985. While Gulf hypoxia has been systematically mapped only since 1985, its presence on the Louisiana continental shelf has been documented since the early 1970s (Figure 2). Continental shelf hypoxia was first reported during 1972–1974, with severely oxygen-depleted bottom waters found at coastal stations in August 1972 and July 1973, and in widespread offshore locations between Barataria Bay and Timbalier Bay at depths of 10–20 meters from May 1973 to May 1974. Surveys to document the suspected widespread occurrence of hypoxia resulted in reports of hypoxia off Terrebonne Bay in March 1975, over a fairly large area off Barataria Bay and Terrebonne Bay in July 1975, at one station off

Terrebonne Bay in July 1976, and in the Mississippi River bight and west of the Atchafalaya delta in September 1975, July 1975, and August 1976.

Hypoxia was documented at several stations between April 1978 and January 1979 and was assumed to be present in June, July, and August 1978, when benthic fauna were depauperate. Oxygen-depleted bottom waters in August and September 1978 covered a moderately large area on the shelf from the Mississippi River bight to the Isles Dernieres and in isolated areas off Atchafalaya Bay. Hypoxia was documented in isolated locations on the Louisiana and Texas shelf in the months of June, July, and August each year from 1980 through 1984. These reports of hypoxia were coincidental to the primary purposes of groundfish surveys and environmental assessments of oil and gas production activities.

Mapping Gulf hypoxia: 1985–2000. Gulf hypoxia has been systematically mapped every year at midsummer since 1985, usually from mid-July to early August (Figure 3). This process has made possible an ongoing description of the hypoxia's dimensions and dynamics. Multiple cruises in July of 1993 and 1994 over periods of 2 to 4 weeks demonstrated that hypoxia persists over large areas although its spatial configuration varies. Time or other logistical constraints often prevented complete mapping of the hypoxic zone, either in the offshore direction or to the west, and shallow waters prevented ship navigation close to shore. Thus, these surveys probably underestimated the extent of bottom-area hypoxia.

More frequent sampling along transect C on the southeastern Louisiana coast (the location indicated on the upper panel of Figure 3) indicates that critically depressed dissolved-oxygen concentrations occur below the pycnocline from as early as late February through early October and nearly continuously from mid-May through mid-September (Rabalais et al. 1999). Hypoxia tends to be patchy and ephemeral in March, April, and May. It is most widespread, persistent, and severe in June, July, and August, when changes in its configuration occur in response to winds, cur

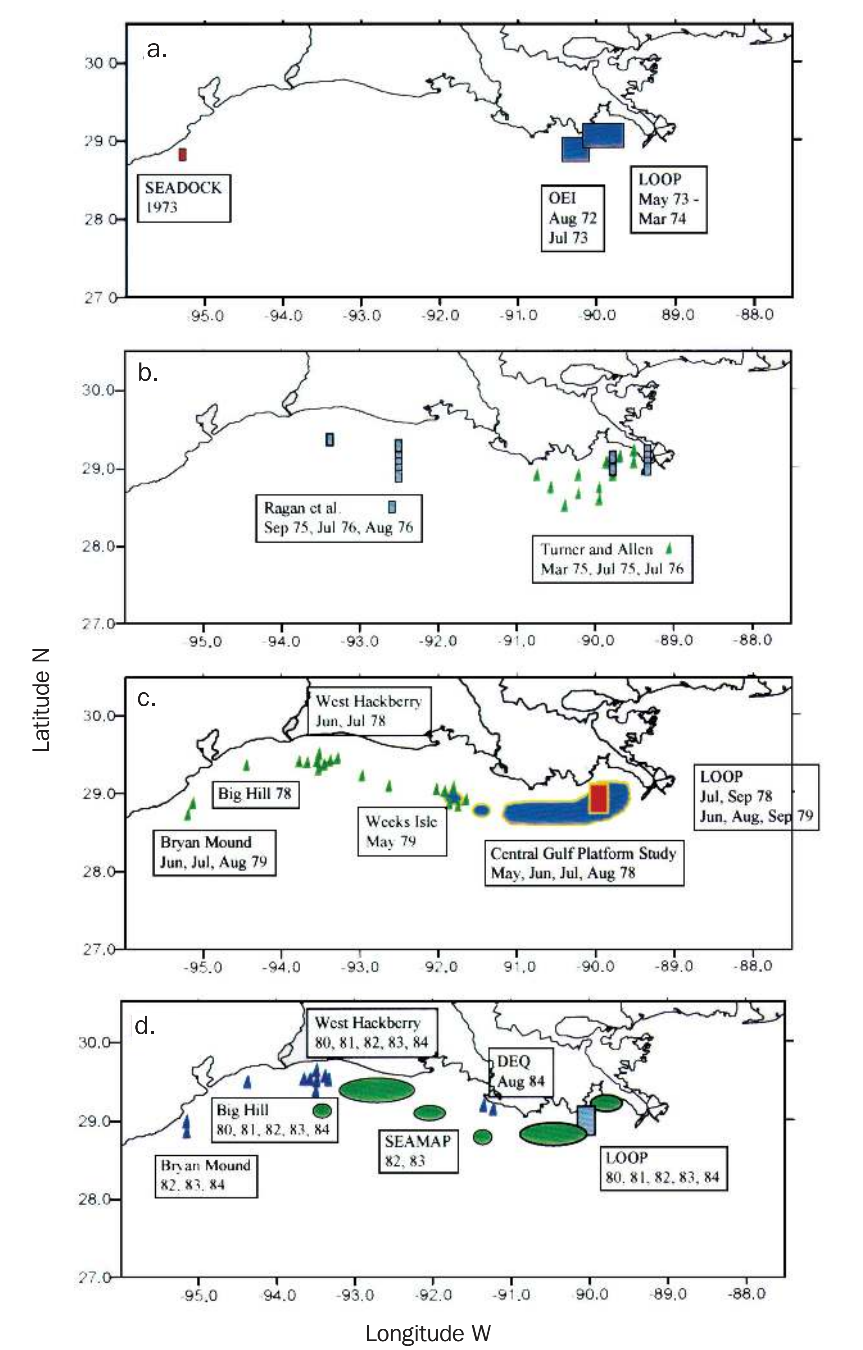

Figure 2. Reports of hypoxia: Summary of studies, locations, and dates. Panel a, Seadock (Oetking et al. 1974) and LOOP, Louisiana Offshore Oil Port (Turner et al. 1998b); sites of proposed offshore oil offloading facilities; and OEI, Offshore Ecology Investigation (Oetking et al. 1974, Ward et al. 1979). Panel b, Ragan et al. (1978) and Turner and Allen (1982). Panel c, Central Gulf Platform Study (Bedinger et al. 1981) is in blue; Strategic Petroleum Reserve Program is identified by green triangles (Jackson and Faw 1980, Harper et al. 1981, Kelly et al. 1983, 1984, Gaston 1985, Pokryfki and Randall 1987); and continued monitoring at LOOP, red rectangle (Turner et al. 1998b). Panel d, SEAMAP (Southeast Area Monitoring and Assessment Program) groundfish surveys, ovals (Gulf States Marine Fisheries Commission 1982, Leming and Stuntz 1984, Renaud 1986, Craig et al. 2001); continued Strategic Petroleum Reserve Program, purple triangles; and continued LOOP, rectangle.

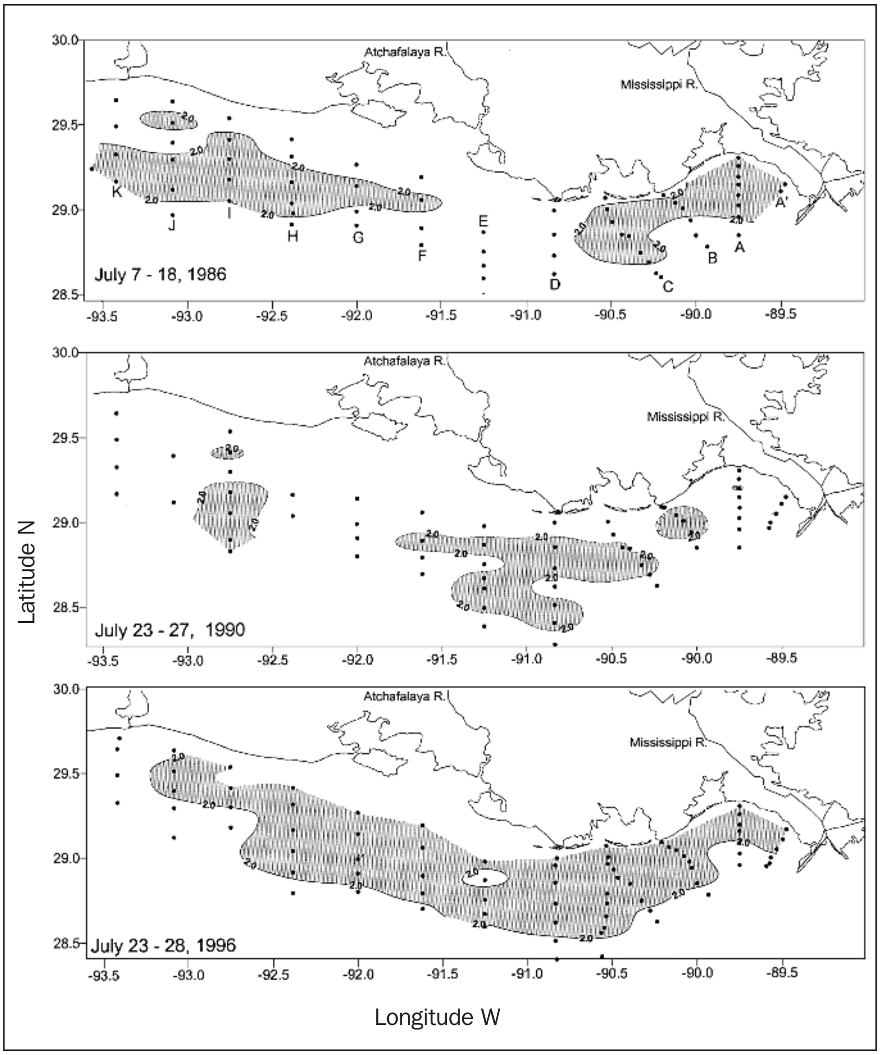

Figure 3. Midsummer distribution of bottom water with less than 2 mg per L dissolved oxygen. From Rabalais et al. 1991, 1999.

rents, and tidal advection. The persistence of extensive and severe hypoxia into September and October depends on the timing of the breakdown of vertical stratification by winds from either tropical storms or the passage of cold fronts. Hypoxia is rare in late fall and winter.

Hypoxia occurs not only at the bottom near the sediments but well up into the water column. Depending on the depth of the water and the location of the pycnocline, hypoxia may encompass from 10% to over 80% of the water column, but more typically constitutes only 20% to 50%. At the upper end of this range, hypoxic waters may reach to within 2 m of the surface in a 10-m water column, or to within 6 m of the surface in a 20-m water column. These hypoxic bottom waters are generally distributed from near shore to as far as 125 km offshore and in waters up to 60 m deep, but more typically between depths of 5 and 30 m.

Midsummer hypoxic zones that occurred between 1985 and 1992 generally formed in two distinct areas west of the Mississippi and Atchafalaya River deltas, together averaging 8000 to 9000 km^2 (Figure 3). In 1988 (a drought year in the Mississippi River basin), reports of the presence of hypoxia were confined to a single station off Terrebonne Bay. Since the Great Mississippi River Flood of 1993, midsummer hypoxia has formed a single contiguous zone across the Louisiana shelf, covering between 16,000 and 21,000 km^2 during 1993–1997 and in 1999 and 2001. The 1998 hypoxic zone was atypically concentrated in water deeper than usual on the eastern and central Louisiana shelf, and the relatively smaller extent in 2000 (4400 km^2) was proportional to the reduced discharge and nutrient flux that year. The average post-1992 hypoxia area covered twice the average observed between 1985 and 1992. The largest area mapped to date was 20,700 km^2 in July 2001 (Rabalais 2001).

Hypoxia is observed most frequently directly down-current (west) from the discharges of the Mississippi and Atchafalaya rivers (Figure 4), as are other biological properties (e.g., elevated surface-water nutrient concentrations and chlorophyll *a* biomass) (Rabalais et al. 1996, 1999). There are strong statistical relationships between either river discharge or nitrate flux and primary production, net production, and hypoxia in the area between the Mississippi River and transect C off Terrebonne Bay (Justic et al. 1993, 1997, Lohrenz et al. 1997). Similar strong statistical relationships exist between Atchafalaya River dis-

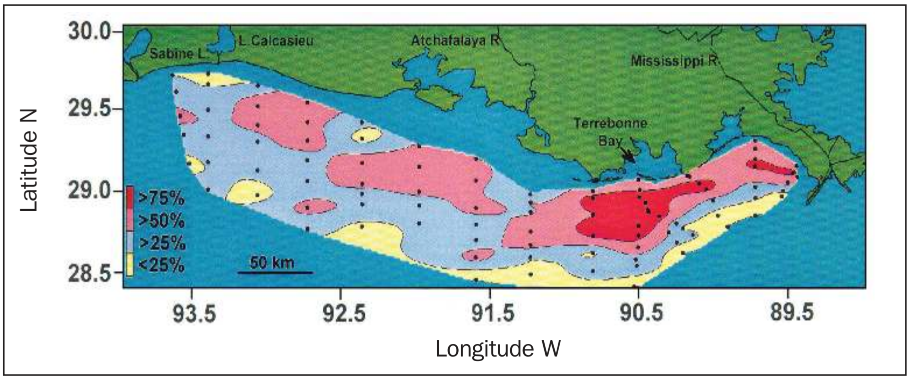

Figure 4. Frequency of occurrence of midsummer hypoxia over the 60–80-station grid, 1985–2001. Modified from Rabalais and Turner 2001a.

charge and hypoxia on the southwestern Louisiana shelf (Pokryfki and Randall 1987). These strong empirical relationships are but one of the lines of evidence linking river nutrient flux (primarily nitrate) and hypoxia extent and distribution.

Historical perspective: Has hypoxia always been there?

The waters of the northern Gulf of Mexico stratify vertically each spring and summer. The fresher river waters are warmed by solar heating to create a lighter, less dense layer of surface waters over colder, saltier bottom waters. This stratification prevents significant oxygen penetration from the atmosphere and photosynthetic production in the surface waters to the bottom waters. Because the volume of freshwater and nutrients delivered by the Mississippi River to this stratified coastal system is large, one might expect hypoxia to develop naturally and to have always been a significant feature of this system. Because relevant water column data do not exist before 1972 and systematic, shelfwide cruises did not start until 1985, the sediment record has been used to evaluate paleoindicators of long-term transitions related to eutrophication and oxygen conditions beneath the Mississippi River plume. Looking down-core through marine sediments is equivalent to looking back in time. The sediment cores, taken from several locations and depths between the Southwest Pass of the Mississippi River and transect B (location shown in the upper panel of Figure 3), and from both within and outside areas where present-day hypoxia occurs more than 50% of the time (Figure 4), provide historical records going back several centuries (data since 1900 are illustrated in Figure 5). These records reflect conditions extant in bottom waters at the time the sediment was deposited and thus provide clues to temporal changes in biogeochemical conditions.

Figure 5 shows time courses for several indicators of algal production and oxygen conditions. The mineral glauconite forms under reducing conditions in sediments, and its abundance is an indication of low oxygen levels. (Glauconite can also form in reducing sediments whose overlying waters have levels of dissolved oxygen above 2 mg per L.) The average proportion of glauconite in the coarse fraction of sediments (Figure 5b) was approximately 6% from 1900 through a transition period between 1940 and 1950, when it increased to approximately 13%. This suggests that while hypoxia might have existed at some level before the 1940–1950 period, it has intensified since then.

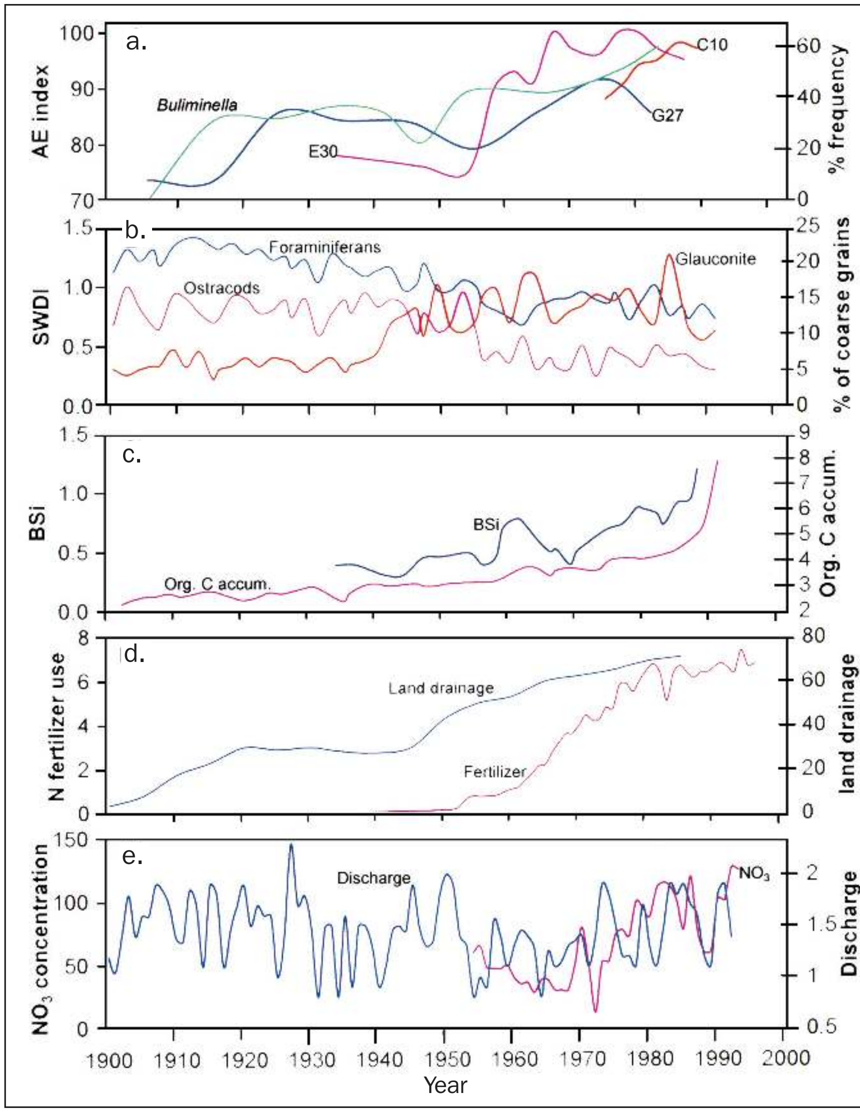

Figure 5. Changes since the beginning of the 20th century in indicators of Gulf of Mexico productivity and oxygen stress and Mississippi River basin landscape use and riverine fluxes. Panel a, A-E index for cores C10 (3-year running average), E30, and G27 (Sen Gupta et al. 1996); percentage frequency of Buliminella *in core G27 (Rabalais et al. 1996). Panel b, SWDI (Shannon-Wiener Diversity Index) for foraminiferans and ostracods (Nelsen et al. 1994; TA Nelsen [National Oceanic and Atmospheric Administration, Miami, Florida], personal communication, 1999); percentage of glauconite in coarse-grain sediment (Nelsen et al. 1994). Panel c, BSi (biologically bound silica, frequency) for core E30 (Turner and Rabalais 1994); organic carbon accumulation (mg · m^{-2} · yr^{-1}) (Eadie et al. 1994). Panel d, nitrogen fertilizer use in the Mississippi River basin (millions of metric tons per year) (Goolsby et al. 1999); land drainage (millions of acres) (Mitsch et al. 2001). Panel e, nitrate concentration (μM) in the lower Mississippi River (Turner et al. 1998a); lower Mississippi River discharge (10,000 m^3 per second; Bratkovich et al. 1994).*

Benthic foraminiferans and ostracods are also useful indicators of reduced oxygen levels because oxygen stress decreases their diversity. Foraminiferal diversity has decreased since the early 1940s, and ostracodal diversity since the early 1950s (Figure 5b). While present-day foraminiferal diversity is generally low in the Mississippi River bight, comparisons among assemblages from areas with different levels of oxygen depletion indicate that the dominance of *Ammonia parkinsoniana* over *Elphidium* spp. (the ratio between the two is called the "A-E index") was much more pronounced in oxygen-depleted waters. The A-E index has also proven to be a reliable oxygen-stress signal in other coastal areas (e.g., Chesapeake Bay, Karlsen et al. 2000; and Long Island Sound, Thomas et al. 2000). Significant changes in the A-E index after the 1950s suggest increased intensity or duration of oxygen stress over the last half-century (Figure 5a). *Buliminella morgani*, a hypoxia-tolerant species of foraminiferan known only from the Gulf of Mexico, dominates the population (accounting for more than 50% of individuals in a sample) within areas of chronic seasonal hypoxia; it has become markedly more prevalent in recent decades (Figure 5a). *Quinqueloculina* sp. (a hypoxia-intolerant foraminiferan) was a conspicuous member of the fauna from 1700 to 1900 (Rabalais et al. 1996) but has been absent since 1900, indicating that oxygen stress was not a problem before that time.

Sediment core analyses also document increased eutrophication and organic matter sedimentation in bottom waters since the 1950s, with the changes being more apparent in areas of chronic hypoxia and coincident with the increasing nitrogen loads from the Mississippi River system. The evidence is provided by increased accumulation of diatom remains (biologically bound silica, BSi) and marine-origin carbon accumulation in the sediments (Figure 5c). Because there have been no significant increases in riverine loads of either organic carbon or silica since 1950 (Turner and Rabalais 1991, Goolsby et al. 1999), one can reasonably infer that increases in sediment BSi since the 1950s are due to *in situ* production of marine diatoms. Stable carbon isotope analyses also indicate that the accumulated sediment carbon originated primarily from marine phytoplankton (Eadie et al. 1994, Turner and Rabalais 1994).

These indicators of oxygen conditions over the last century reveal an overall increase in intensity or duration of continental shelf oxygen stress that seems especially severe since the 1950s. These indicators parallel the increases in indicators of the primary production that leads to accumulated organic matter in the sediments (e.g., diatom remains and accumulated carbon of marine origin).

What causes Gulf of Mexico hypoxia?

Two principal factors lead to the development and maintenance of hypoxia on the Louisiana continental shelf: (1) The oxygen-consuming decomposition of phytoplankton produces organic carbon that sinks to bottom waters, and (2) a physically stratified water column prevents oxygen replenishment from the surface. The heavy freshwater discharge, general circulation patterns, and Louisiana coastal current produce a vertically stratified system for much of the year, interrupted by occasional tropical storms and winter cold fronts. This persistent stratification isolates the warmer, fresher surface water from the colder, more saline bottom water. With the effects of these physical conditions understood, the remaining issue has been to determine the source of increased organic carbon loading. There are three potential sources: (1) organic carbon from the Mississippi and Atchafalaya Rivers, (2) organic carbon from degrading coastal wetlands, and (3) organic carbon produced *in situ* by marine phytoplankton.

While information gaps still exist and other factors discussed below may contribute to hypoxia, the overwhelming scientific evidence indicates that marine phytoplankton production, driven by nitrogen loading from the Mississippi River drainage basin, is the primary source of the organic carbon that decomposes and drives the onset and duration of hypoxia in the northern Gulf of Mexico (Table 1). Nutrients, primarily nitrogen, supplied by the Mississippi River stimulate phytoplankton production in the warm surface waters of the Gulf. Phytoplankton not consumed by zooplankton grazers and fecal material produced by those grazers sink into bottom waters, where they are decomposed by bacteria. When this oxygen-consuming decomposition outpaces the rate of oxygen diffusion from the surface, which is inhibited by stratification, then oxygen concentration decreases. When decomposition and vertical stratification persist through the summer, oxygen concentrations decrease below critical thresholds for most living organisms.

The compelling evidence for the close coupling of riverborne nutrients and primary production, net production, vertical carbon flux, and hypoxia derives from well-documented experiments, empirical relationships, seasonal oxygen and carbon budgets, time-series analyses, models, and comparisons with other coastal regions, and are summarized in Rabalais et al. (1999, forthcoming) and in Table 1.

Nutrient sources: Watershed and land-use change

Increased marine productivity and worsened hypoxia parallel the increases in nitrate loads to the Gulf since the 1950s (Figure 5e), so it is important to examine the potential causes of that nitrate increase. In addition to the steady growth of the human population within the Mississippi basin, and the resultant increases in inputs of nitrogen through municipal wastewater systems, three other forms of human activity that have changed the natural functioning of the Mississippi River system warrant particular consideration.

First, flood control and navigational channelization are clearly important watershed alterations. Most of these occurred well before the 1950s, whereas the significant changes in Gulf productivity and indicators of low oxygen levels recorded in the sediments appear to have occurred since then.

Table 1. Evidence for nitrogen-driven phytoplankton production (data adapted from Rabalais et al. 1999, forthcoming).

Temporal scale	Evidence
Days	Bioassay experiments with nutrient additions/deletions
	Simulated *in situ* measurements of primary production across a range of dissolved inorganic nitrogen concentrations
	Short-term primary production models
	Correlation of nitrate with primary production
	Depletion of nitrate and silicate along a salinity dilution gradient
	In situ Redfield ratios
Months	Correlation of primary production with time-lagged nitrate concentration and flux
	Correlation of surface-water net production with time-lagged nitrate flux
	Correlation of surface-water net production and bottom-water oxygen stress with 1- and 2-month (respectively) lagged fresh-water discharge
	Oxygen and carbon budgets
	Carbon-flux relationships with indicators of river discharge and increased surface-water production
	Response of mass-balance model to reductions in nitrogen load
Years	Sediment cores and coincidental timing with increased nitrogen loading
	Increase in accumulation of marine-source carbon
	Increase in silicate-based productivity
	Increase in foraminiferal A-E index (increased carbon accumulation and worsening oxygen stress)
	Decrease in diversity of benthic ostracod and foraminiferan communities
	Loss of oxygen-intolerant foraminiferans and increase in oxygen-tolerant forms
	Response of biological-physical coupled model to increased inputs of nitrate
	1998, 1992, or other low-discharge years for nonevents; variability in spring discharge, predicted carbon flux, or stratification (or a combination of these indicators)

Second, other significant landscape alterations (e.g., deforestation, conversion of wetlands to cropland, loss of riparian zones, expansion of artificial agricultural drainage) removed most of the Mississippi basin's natural capacity to withhold nutrients from runoff draining into the Mississippi tributaries and main stem. There was an increase in the area of land artificially drained between 1900 and 1920 and another significant upswing in drainage activity during 1945–1960 (Figure 5d).

Third, there was a dramatic increase in nitrogen input into the Mississippi River drainage basin, primarily from fertilizer application, between the 1950s and the 1980s (Figure 5d, 5e). Even as the increase in drainage and fertilizer application dramatically boosted crop production, it also caused significant increases in riverine nitrate concentrations and flux to the Gulf (Turner and Rabalais 1991, Goolsby et al. 1999). The annual flux of nitrogen to the Gulf tripled between 1955 and 1970 and between 1980 to 1996 to the present average of 1.6 million metric tons per year, with 61% of that flux in the form of nitrate. Ninety percent of the nitrate inputs to the basin are from nonpoint sources, of which 74% are agricultural in origin. In addition, 56% of the nitrate enters the Mississippi River system north of the confluence with the Ohio River. Organic nitrogen measurements were not regularly made before 1973, but they show no trend since then. Both stream flow and nitrate flux have become much more variable in the last quarter-century (Figure 5e; Goolsby et al. 1999).

Other factors contributing to changes in the hypoxic zone

While only increased nitrogen loads from the Mississippi River system can account for the changes in the hypoxic zone since the 1950s, other factors may contribute to its growth, dynamics, and decline. Several of those factors were analyzed and discussed during the scientific and public policy debates leading to formulation of the *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001), which was submitted to Congress in 2001. Those factors include flux of poorly oxygenated waters from the deep Gulf, river loading of organic carbon, channelization and coastal wetland loss, nitrogen flux from the atmosphere or deep Gulf waters, and climate-induced alterations in water flux from the Mississippi River basin. We emphasize that these do not constitute competing hypotheses, but rather a set of contributing factors. The task was to determine which were the most important.

Flux of poorly oxygenated water from offshore.

Early researchers (cited in Turner and Allen 1982) proposed that intrusion of water from a poorly oxygenated layer located in deeper, offshore waters onto the continental shelf was the source of shelf bottom-water hypoxia. This mechanism resurfaced more recently in public comments as part of the public policy debate leading to the action plan. This persistent, offshore, low-oxygen layer at depths of 400–700 m was first described in the mid-1930s following data collection in the Gulf by a research vessel, the M/V *Atlantis* (Conseil 1936); however, there are no oxygen values less than 2 mg per L in that data set. In addition, oxygen values less than even 4.3 mg per L were found far off the continental shelf at depths of 250–600 m in a water column that was considerably deeper (Figure 6), with no physical connection between this deep oxygen-minimum zone and the hypoxic layer on the shelf (Pokryfki and Randall 1987, Rabalais et al. 1991). In addition, oxygen consumption rates in this deep layer are insufficient to account for the observed decline in oxygen concentrations on the shelf (Turner et al. 1997).

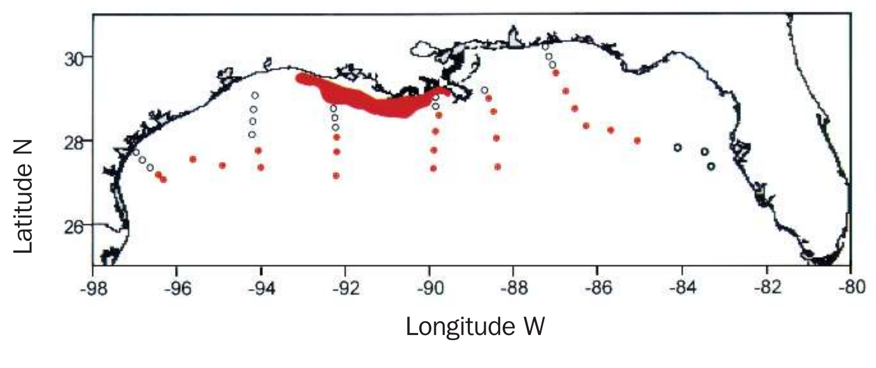

Figure 6. Stations from the M/V* Atlantis *surveys during 1935 of the Gulf of Mexico north of 27° N. Open black circles indicate stations with midwater dissolved oxygen concentrations greater than 3 cubic centimeters per L (equivalent to 4.3 mg per L), and closed red circles, less than 3 cm^3 per L, compared to the hypoxic zone of July 1996 (Figure 3). M/V* Atlantis *data are from Conseil permanent international pour l'exploration de la mer (1936); for July 1996, from Rabalais et al. 1999.

Organic carbon load. The organic carbon supplied by the Mississippi River has been proposed as a cause of Gulf hypoxia (Carey et al. 1999). The suspended sediment load in the river has decreased by about half since the 1950s, so the particulate organic load that could settle on the Louisiana shelf has also most likely decreased since then. Also, the distances particulate organic carbon would need to be transported to affect the large area of hypoxia are too great to provide a significant load. In addition, stable carbon isotope data for sediment cores from the hypoxic zone indicate that 80% of the accumulated sediment carbon is of marine, not terrestrial, origin. The scientific consensus is that direct discharge of organic carbon is a relatively small factor in hypoxia.

Channelization and coastal wetland loss. Although significant over-bank flooding was once common in the Mississippi River delta, the leveeing of the river in the aftermath of the floods of 1927 occurred well before nitrate loads and sedimentary indicators of hypoxia began to rise, in the 1950s. The carbon released from coastal wetland loss in Louisiana (65 km^2 per year from 1983 to 1990) contributes a relatively small amount of organic carbon to the hypoxic region. Furthermore, stable carbon isotope analyses indicate that wetland organic carbon accumulation is confined to a narrow nearshore band, whereas the sedimentary carbon in the region of hypoxia derives primarily from marine phytoplankton production *in situ* (Turner and Rabalais 1994).

Atmospheric and offshore nitrogen. The Mississippi and Atchafalaya Rivers are easily the most significant deliverers of nutrients to the northern Gulf of Mexico (Dunn 1996). Direct atmospheric deposition to the offshore surface waters accounts for only 1% to 2% of the total nitrogen budget (Goolsby et al. 1999). The upwelled flow of nitrate from deeper waters may be important at the shelf edge at depths of 100 m, but there is inadequate physical advection of deep bottom waters onto the inner shelf to supply the nutrients needed to support the observed high levels of primary production. Groundwater discharges directly to the Gulf are unlikely to be important because of the lack of shallow aquifers along the Louisiana coast and the low potential for transfer in a cross-shelf direction. The best current knowledge is that the outflows of the two rivers dominate the nutrient loads to the continental shelf where hypoxia is likely to develop (Rabalais et al. 1999).

Climate change. Because the amount of freshwater delivered to the northern Gulf of Mexico influences both the nitrogen load and the intensity of salinity stratification on the shelf, climate-induced variability in river discharge will influence the extent and severity of hypoxia. Annual river discharge since the early 1900s has been highly variable, with discharge increasing by only 15% since 1900 and 30% since the 1950s. This is in contrast to the 300% increase in nitrate load since the 1950s (Turner and Rabalais 1991). Clearly, the most significant factor in the change in nitrate load is the increase in nitrate river concentration, not freshwater discharge. In addition, the change in annual freshwater discharge appears to be due mostly to increased discharge from September to December, a period less important to both the physical and the biological processes that lead to hypoxia development and maintenance.

Science and policy development

Although retrospective analyses revealed century-long changes in the watershed and the Gulf, the most dramatic and accelerating changes have been since the 1950s, when nitrogen loads began to increase, eventually tripling over their historical values. With the causes of hypoxia more clearly defined and the sources of nutrients fairly well understood, the next step was the development of a strategy for reducing nutrient loading to the Gulf. The implementation of a detailed resource management plan remains a daunting task for a watershed covering 41% of the contiguous United States. This region embraces 31 states and the holdings of dozens of Native American tribes and is home to countless legislative, political, institutional, and societal structures. In the early 1990s, a process began that culminated in 2001 with the delivery to Congress of the *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) (Table 2).

Recognizing the problem. The connection between hypoxia and river inputs in general, and between hypoxia and increased nitrate loadings in particular, was made before 1990, but additional research in the early 1990s accumulated compelling evidence of this connection. Subsequently, repeated attempts were made by academic and federal scientists to bring this issue to the attention of managers and policymakers. Some of these efforts followed what Luttenberg and Scavia (1998) refer to alternately as the "packet model" and the "diffusion model" for exchange at the science–policy interface. The packet model includes development and delivery of specific reports and analyses. These reports and analyses are occasionally requested by decisionmakers and are most often scientific papers, reviews, syntheses, and technical reports. They can be very useful, particularly in the early stages of problem identification. Many such reports and research articles were published between 1990 and 1996 (e.g., references in Rabalais et al. 1999, Wiseman et al. 1999, and Rabalais and Turner 2001b), and they helped lay a solid scientific foundation for dialogue among policymakers.

The diffusion model encourages frequent interactions and exchanges among scientists and managers. The National Oceanic and Atmospheric Administration (NOAA) Nutrient Enhanced Coastal Ocean Productivity (NECOP) study, conducted between 1990 and 1996 (Wiseman et al. 1999), is an example of this mode of exchange. NECOP fostered communication among scientists and managers in its analyses and synthesis phase. NECOP's advisory groups and review panels, including the National Research Council and state and federal resource managers, helped shape the NECOP research agenda and increased the flow of information gathered during the program. In addition, NECOP representatives and other scientists serving on regional management and planning committees (e.g., the intergovernmental Gulf of Mexico Program) helped disseminate information on hypoxia and its connection to the Mississippi River.

Although some progress was made with both the packet and the diffusion models, it was a third model that most effectively brought this scientific knowledge to the attention of managers and policymakers and that created the final impetus for action. "Triangulation" brings a third party to the table—public stakeholders. Releasing annual maps of the extent of the hypoxic zone, beginning in 1993, captured the attention of the press and then the public, including nongovernmental stakeholders. In 1995, the Sierra Club Legal Defense Fund (now the Earthjustice Legal Defense Fund) led 17 stakeholder groups in petitioning officials of the US Environmental Protection Agency (EPA) and the state of Louisiana to convene a general management conference under section 319(g) of the Clean Water Act. In coordination with other agencies, EPA responded by initiating an exchange of scientific knowledge and public information through a series of workshops and symposia. The stakeholders' petition consequently got the attention of managers and policymakers.

A sequence of conferences that began in 1995 in New Orleans, and the following year in Davenport, Iowa, conveyed information on the dynamics and effects of hypoxia, links to nutrient loads from the Mississippi River system, and management activities under way in the basin. Soon after these public fora, EPA convened meetings of high-ranking federal principals to start the policy dialogue and asked the White House Office of Science and Technology Policy to conduct what would be the Integrated Assessment of Hypoxia in the Northern Gulf of Mexico (Committee on Environment and Natural Resources 2000). These gatherings of federal officials were widened in December 1997 to include state and tribal officials; the combined federal, state, and tribal task force met seven times through 2000 to develop the action plan.

It took all three models of communication to move from scientific insight to identification and recognition of the problem. Reports and research papers (packets) formed the scientific underpinnings for the overall understanding of hypoxia in the Gulf of Mexico. Enhanced dialogue among scientists and managers (diffusion) increased the awareness of those managers and helped hone the science-based questions asked by the scientists. Finally, it was a public, now directly aware of the issue (triangulation), and the stakeholder groups representing them, that raised the issue to a level requiring a policy response.

Table 2. Steps toward nutrient policy development.

Date	Action
1972–1974	Hypoxia first documented in the northern Gulf of Mexico
1985	Comprehensive assessment of Gulf hypoxia begins
1990–1995	National Oceanic and Atmospheric Administration (NOAA) Coastal Ocean Program builds upon existing science with expanded research in the northern Gulf of Mexico
1993–1994	Public interest raised through press reports and public outreach
1995	Nongovernmental organizations petition the US Environmental Protection Agency (EPA) and the governor of Louisiana for a management conference under section 319(g) of the Clean Water Act
1995–1996	Public education and outreach begin with hypoxia conferences in New Orleans, LA, and Davenport, IA
1996	EPA convenes Mississippi River/Gulf of Mexico Watershed Nutrient Task Force
1997	Congressional Committee on Environment and Natural Resources initiates hypoxia assessment
1998	Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA, PL 105-383) calls for "Integrated Assessment and Action Plan"
1999	Congressional Committee on Environment and Natural Resources hypoxia assessment is completed
2000	Integrated assessment is completed. Task force reaches consensus and action plan is completed
2001	Action plan delivered to Congress and plans to continue the work of the task force are under development

The integrated assessment. Although many sources informed the action plan, the integrated assessment became the centerpiece of scientific input because it was

- broadly integrative and synthetic
- responsive to the policy-relevant questions
- based on peer review and public participation
- based on high-quality monitoring data
- predictive

The integrated assessment was *broadly integrative and synthetic.* It convened six teams of scientific experts to synthesize decades of research and monitoring on the extent, characteristics, causes, and effects (both ecological and economic) of Gulf hypoxia; the flux and sources of nutrients in the Mississippi River system; the effects of reducing nutrient loads on waters within the basin and in the Gulf; methods for reducing nutrient loads; and the social and economic costs and benefits of reducing those loads. Although the integrated assessment was clearly *policy relevant* in its initiation, it became more so when, in 1998, Congress passed and President Clinton signed into law the *Harmful Algal Bloom and Hypoxia Research and Control Act* (PL 105–383), which codified the assessment's development and established a formal task force (the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force) to deliver an action plan.

Peer view and public participation were keys to strengthening the integrated assessment. Stakeholders played important roles in both the integrated assessment and the action plan. The six technical reports, with a collective authorship of 47 scientists, received peer reviews under the guidance of an independent editorial board composed of highly respected scientists endorsed by both the federal assessment team and the task force. After peer review, the six reports were released for formal public review, which generated hundreds of pages of comment. Those comments and the six reports formed the basis of the integrated assessment, which was also released for public comment before completion. (The six reports, the integrated assessment, the public comments, and the responses to those comments are available at *www.nos.noaa.gov/Products/pubs_hypox.html.)*

Consensus on the integrated assessment and action plan was not reached without debate or controversy. Three other significant reports were issued during their development. The report by Carey and colleagues (1999) was commissioned by the Fertilizer Institute, the report by Downing and colleagues (1999) by the Council for Agricultural Science and Technology, and Krug's and Winstanley's report (2000) by the Illinois Council for Food and Agricultural Research. While the integrated assessment and the report by Downing and others came to the same basic conclusion—that nitrogen from the upper Midwest is the primary driver of Gulf hypoxia—the other reports (Carey et al. and Krug and Winstanley) proposed alternatives. Carey and colleagues identified the importance of nitrogen loss from agricultural lands but also suggested that increased water flow and supplies of organic carbon were significant contributors to eutrophication and hypoxia. Krug and Winstanley, conversely, rejected the notion of nitrogen as a driver of Gulf hypoxia. They reported that the waters of the Illinois River basin, prior to European settlement and even into the 19th century, were highly enriched with naturally occurring nutrients, including large quantities of organic matter and inorganic nitrogen, and that release of nitrogen in the course of the original conversion from native prairies to agricultural lands was significant. Krug and Winstanley also claimed that nitrogen fixation on presettlement prairies was greater than present-day nitrogen additions to the basin and that nitrogen concentrations in the Illinois River are lower today than in the 1890s.

Finding common ground among these divergent views helped strengthen the scientific basis for the action plan. Two events shed light on the apparent discrepancies among the reports. The first was a facilitated meeting of scientists that represented the divergent views, as well as those of other experts who were not part of the original debate. Scientists from federal agencies, environmental nongovernmental organizations, and state agencies, as well as academics supported by these groups or by the fertilizer industry, attended the meeting, held in St. Louis in December 1999. Discussions at this meeting focused on questions related to the history of nitrogen flux from the basin, the relative role of terrigenous carbon as a driver of hypoxia, the relationship of nitrogen inputs in the basin to organic nitrogen soil inventories and nitrogen outputs, and the effects of changes in freshwater flows on stratification and hypoxia in the Gulf. The meeting had a few simple ground rules, the most important of which was that arguments had to be factually based (i.e., data to support the arguments were required). The *high-quality monitoring data* used in the integrated assessment formed the basis for much of the debate. Several important conclusions were reached after informative presentations and thorough debate. One was that while flow in the Mississippi/Atchafalaya system increased over the last half of the 20th century, that increase was small (about 30%) compared to the increased flux of nitrate (about 300%). A second conclusion was that while terrestrial organic carbon may contribute to some of the oxygen demand, it is overwhelmed by *in situ* algal production stimulated by the presence of riverine nitrogen.

The issues in Krug and Winstanley (2000) raised considerable interest and concern among the scientists involved in development of the integrated assessment reports and among the scientific community in general. An independent, unsolicited analysis produced by scientists from the University of Illinois (McIsaac et al. 2000) and reviewed by a wide range of other academics shed light on the material in the Krug and Winstanley report. McIsaac and others reanalyzed most of the data and reference material reported in Krug and Winstanley and reported that many references to the early literature were incomplete or misinterpreted. McIsaac and others reached the conclusion that the report "does not provide a scientifically sound basis for characterizing water quality reference conditions." The debate continued with a letter from Winstanley to McIsaac and others *(www.sws.uiuc.edu/docs/hypoxia/*

NRESletter.asp) and a response from McIsaac *(www.nres.uiuc.edu/research/00-03_append.html)*. The views espoused by Krug and Winstanley became outliers in the larger scheme, however, and ultimately did not make a major contribution to the final discussions of management actions.

The action plan. Dialogue among scientists, members of the task force, and the public continued to strengthen the policy relevance of the integrated assessment. While it was being developed, the task force held seven public meetings: in Washington, DC, New Orleans, Minneapolis, Memphis, Chicago, St. Louis, and Baton Rouge. Each meeting provided a forum for exchange among the task force members, the participants in the scientific assessment, and a range of stakeholders on issues related to the science, views on action strategies, and the implications for various alternative implementation strategies. The meetings were well attended by task force members, staff, and the public. There were often lively debates among environmental, agricultural, economic, and scientific interests. A draft of the action plan was made available for public comment prior to the final meeting of the task force, which was held in October 2000. At that meeting, unanimity was reached on steps to improve water quality within the Mississippi River basin and the northern Gulf of Mexico (Table 3). The action plan was cleared by the state, tribal, and federal agencies and delivered by President Clinton to Congress in January 2001. As of December 2001, there were indications that the administration of George W. Bush intended to reconvene the task force to move forward on implementing the action plan.

That so many disparate groups and individuals came to consensus is commendable, if not surprising, and speaks to the perseverance and dedication of many people; however, no one was completely satisfied with the result. Some wanted more stringent and higher nutrient reduction goals, while others wanted only qualitative goals. Some participants wanted regulations; others wanted voluntary, incentive-based actions.

The compromise included a quantitative environmental goal of reducing the 5-year running average of the areal extent of Gulf hypoxia to less than 5000 km^2 by 2015 (Figure 7), consistent with historical data and *model predictions*. The action plan also recognizes that a 30% nitrogen load reduction is probably needed to reach that goal and that implementation should be based primarily on voluntary, incentive-based subbasin strategies.

According to the action plan, these voluntary and incentive-based activities, designed within a series of subbasin strategies, would include best management practices on agricultural lands, wetland restoration and creation, river hydrology remediation and riparian buffer strips, and stormwater and wastewater nutrient removal (Mitsch et al. 2001). These subbasin efforts, which are intended to add up to an overall nitrogen load reduction of 30%, will take place within a broader framework of increasing demand for agricultural products and energy and within highly variable environments in the Mississippi River basin and the northern Gulf of Mexico.

Adaptive management. While steady-state mass balance models for the Louisiana shelf indicate that hypoxia can be reduced to varying degrees by proportional reductions in nutrient loads (Limno-Tech 1995, Brezonik et al. 1999), experience from other systems and a dynamic biological–physical model for the Louisiana shelf (Justic et al. 1997) indicate that it may take several years or longer to detect a marine response to nutrient load changes. Also, if a new steady state within the basin exists that balances stored soil nitrogen, inputs, and flushing in response to

Table 3. Task Force action plan goals for improvement of water quality (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001).

Coastal goal[a]	By 2015, subject to the availability of additional resources, to reduce the 5-year running average areal extent of the Gulf of Mexico hypoxic zone to less than 5000 km^2 (Figure 7) through implementation of specific, practical, and cost-effective voluntary actions by all states and tribes and to address all categories of sources and removals within the Mississippi–Atchafalaya basin so as to reduce the annual discharge of nitrogen into the Gulf
Within-basin goal	To restore and protect the waters of the 31 states and tribal lands within the Mississippi–Atchafalaya basin through implementation of nutrient and sediment reduction actions to protect public health and aquatic life as well as reduce negative impacts of water pollution in the Gulf of Mexico
Quality-of-life goal	To improve communities and economic conditions across the Mississippi–Atchafalaya basin, in particular the agriculture, fisheries, and recreation sectors, through improved public and private land management and a cooperative, incentive-based approach

Note: The Task Force is composed of federal agencies (Environmental Protection Agency, Department of Agriculture, National Oceanic and Atmospheric Administration, Department of Interior, Army Corps of Engineers, Department of Justice, Office of Science Technology and Policy, Council on Environmental Quality), state governments (Arkansas, Illinois, Iowa, Louisiana, Minnesota, Mississippi, Missouri, Tennessee, Wisconsin), and tribal organizations (Mississippi Band of Choctaw Indians, Prairie Island Indian Community).

a. To reach the coastal goal, task force members agreed to a series of steps to organize around subbasin strategies for reducing nitrogen loads to the Gulf by 30%, primarily through voluntary, incentive-based action mediated by educational activities.

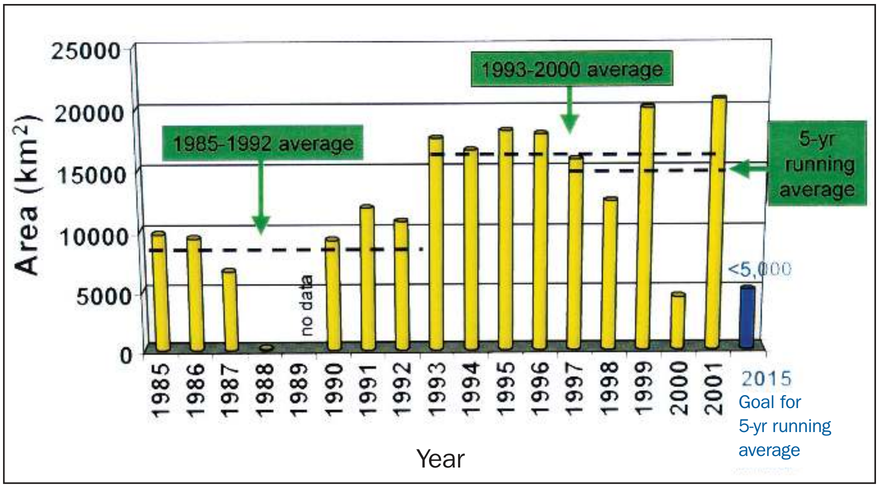

Figure 7. Estimated bottom areal extent of hypoxia (dissolved oxygen less than 2 mg per L) for midsummer cruises, 1985–2001, and 2015 goal of 5000 km² or less, with long-term average sizes superimposed. From Rabalais and colleagues 1999.

precipitation and climatic variability, management actions may not result in reduced nitrogen flux to the Gulf for many years. In recognizing these significant potential time delays, the action plan called for a long-term adaptive management strategy (Figure 8) linking management actions with enhanced monitoring, modeling, research, and a commitment to reassess conditions in 2005 and subsequently at 5-year intervals. Also imperative within this long-term strategy is a public education component that continues communication with stakeholders about management successes, system recoveries, and any seeming lack of progress.

Conclusions

Decades of research and monitoring in the Gulf of Mexico and the Mississippi River basin, synthesized through development of the *Integrated Assessment of Hypoxia in the Northern Gulf of Mexico* (Committee on Environment and Natural Resources 2000), provided a solid scientific basis for reducing Gulf hypoxia and improving basin water quality. The resulting *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) both identifies a quantitative goal for a reduced hypoxic zone and recognizes that to achieve that goal, a 30% reduction in the nitrogen load is needed. The action plan recognizes that all nitrogen sources should be included in the strategy. Because 74% of the nitrate load is from agricultural nonpoint sources, and because 56% of the total nitrate load originates north of the mouth of the Ohio River, it is clear that nitrogen reductions in the subbasins of the upper Midwest will be crucial to effective implementation of the plan.

While no one was fully satisfied with the result, reaching agreement on actions at the massive scale represented by the Mississippi River basin is a tribute to the openness of the process and the strength of the science. Stakeholders brought the issue to policymakers, and both groups' involvement throughout development of the integrated assessment and the action plan ensured that their interests were balanced in coverage and perspective, leading ultimately to acceptance by most participants. The science base was solid because the integrated assessment synthesized high-quality, peer-reviewed monitoring and research results in a policy-relevant manner; responded to public comment; and provided predictions that were tempered with an appropriate measure of uncertainty. The scientific debates throughout the process made it clear that science is an evolving state of knowledge that at times warrants action but often cannot provide absolute certainty.

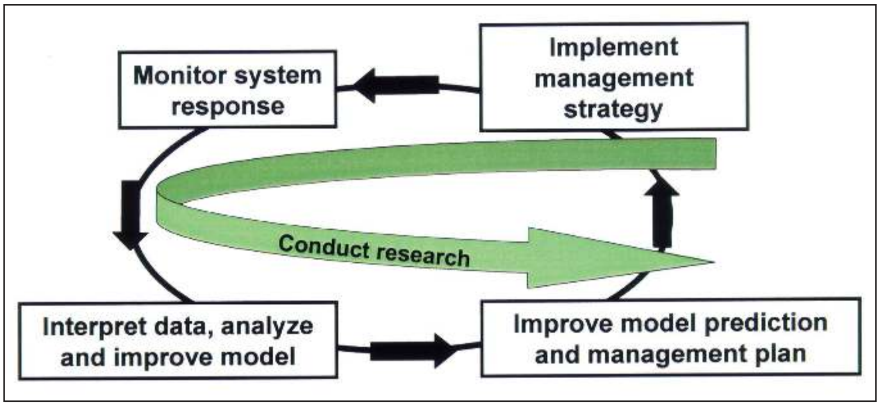

Figure 8. Adaptive management framework that connects monitoring, analysis, and management actions with continuous feedback for improvement. New understandings from research should be interwoven throughout the process (Herb Buxton, US Geological Survey, in Congressional Committee on Environment and Natural Resources 2000).

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