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presents

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Ecosystem Science Informs Sound Policy... or Does It?

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Abstract

In a “perfect” world, ecosystem science would inform policy that, in turn, conserves ecosystem stability and function, as well as maintains a healthy social and economic status for a public that depends on healthy ecosystems as a component of economic health and stability. Coastal hypoxia (“oxygen deficiency”) and its determinants, as identified in ecosystem research, provide an ideal opportunity to explore how ecosystem research informs management decisions.

Long-running studies have been conducted in many coastal ecosystems, including the northern Gulf of Mexico “Dead Zone,” that were initiated by the scientific curiosity of a few or by the concerted efforts of state and federal agencies. In the northern Gulf of Mexico, efforts by the National Oceanographic and Atmospheric Administration (NOAA) supported research on nutrient-enhanced coastal ocean productivity. Subsequent legislation to study hypoxia and harmful algal blooms led to assessments of hypoxia in the Gulf of Mexico and other coastal waters nationwide. The results are consistent: excess nutrients lead to eutrophication (enhanced carbon production and accumulation) and negative impacts, such as hypoxia (reduced oxygen levels) or anoxia (no oxygen) and noxious or harmful algal blooms.

Ecosystem research programs led us from early hypotheses concerning increased nitrogen loads in the Mississippi River (circa 1973),

nutrient enrichment, and Gulf of Mexico productivity, followed by nutrient over-enrichment and the potential negative effects, including hypoxia. Ecosystem research helped inform management of nutrient inputs and their mitigation, forecasting capabilities, and considerations under climate change. The policy decisions seem clear, but the linkages among science, policy, and management decisions are tempered, as always, by stakeholder interests.

Introduction

My pleasure this evening is to be the 2008 recipient of the Athalie Richardson Irvine Clark Prize. This is truly an honor, and I am awed to be among the list of prior awardees. I am also pleased to be the second woman recipient of the Clarke Prize. Most, if not all, of the prior Clarke Prize awardees are distinguished for their technical and engineering solutions to water resource quality. My history is as an aquatic scientist who examines ecosystems and their intricacies both within the ecosystem and with the external forcing factors, including humans.

Little did I know when I fell in love with biology in junior high school that one day I would be an “expert” on anything, let alone transforming – or trying to transform – water quality management policy. It is my strong belief that the research I conduct, mostly with public funds, be translated into knowledge that informs the public and the policy decisions that they make. This evening,

I provide parallel paths of my research career, its incredible path of discovery, and how it relates to water quality issues. Necessarily, the focus will be my favorite research topic, hypoxia (or oxygen depletion), commonly known as the “Dead Zone” in the northern Gulf of Mexico.

My early career in marine invertebrate zoology and habitats, endemic fiddler crab populations, and sea squirt communities of an offshore South Texas reef led to an appreciation of habitat, ecosystems, and their uniqueness and function. My ability in invertebrate taxonomy, which is now an almost extinct skill among young biologists, led to my first job studying the benthic (bottom-dwelling) communities of the South Texas offshore ecosystem. This was my first chance to combine the physical, chemical, and geological components of the ecosystem with the biological communities. From there, it is history. My ecosystem-level integration skills – not my ability to determine the gill surface area of a series of fiddler crab species – led me to Louisiana and a new world of ecosystem-level experiments in progress. Not to mention, the opportunity to inform science policy.

My first employer out of my Ph.D. was Dr. Donald Boesch, Director of the Louisiana Universities Marine Consortium (LUMCON), where 20-plus years later, I am now Director (and have been for the last 3 years). In addition to my exploration of the early life history physiology of decapod crustaceans, Dr. Boesch herded me in the direction of environmental issues for which science could inform management and policy, particularly where relevant to Louisiana.

Being an oil and gas producer in the coastal zone since the 1930s, Louisiana had been disposing of oilfield waste for many years outside of the U.S. Environmental Protection Agency’s (EPA) permit program (National Permit Disposal Elimination System [NPDES]). In hindsight, the EPA, the Louisiana Department of Natural Resources, and the Texas Railroad Commission realized that these practices led to negative impacts on the receiving waters and their living resources.

Funding from both industry and the Minerals Management Service for research provided evidence of contamination by highly volatile benzene, toluene, and xylene, and the more persistent alkylated polynuclear aromatic hydrocarbons. This research resulted in the need for NPDES permits for discharges in inshore waters, with the contaminants either being reinjected into the oil formation, transported and disposed offsite, or transported to offshore waters. Findings from offshore disposal sites also resulted in

tighter restrictions for those effluents, and overall healthier marine ecosystems both inshore and offshore. The results of those research programs were not necessarily what the oil and gas industry would have preferred for cheaper operations, but overall the benefits for habitat, water resources, and public health prevailed.

Then begins the ecosystem study to which I have invested my efforts for the last 20-plus years – the linkages of the landscape and land use in the Mississippi River watershed and the quality of the water in the coastal ecosystems adjacent to the Mississippi River in response to changes in the watershed over time. Similar processes occur worldwide in estuaries and large areas of the coastal ocean.

The Clarke Prize identifies me as “the driving force behind identifying and characterizing the dynamics of the large hypoxic region in the Gulf of Mexico,” but I would not be standing here if it were not for the creative and dedicated colleagues who have been instrumental in defining the how, where, when, and why of watershed changes and coastal water quality. It is to them that I dedicate this Lecture. It has truly been a collegial and exciting trip.

Background

The development, extent, and persistence of low oxygen concentrations (hypoxia) in bottom waters of the continental shelf of the northern Gulf of Mexico were unknown until the first systematic mapping and monitoring of oxygen began in 1985 (Rabalais et al., 1991). At that time, shelf hypoxia (defined here as dissolved oxygen levels at or below 2 milligrams per liter [mg l^{-1}], or parts per million [ppm]) was thought to be localized and ephemeral. Since the initial investigations, a large volume of data has been collected and numerous papers and reports have been published that increased our understanding of the seasonal and interannual distribution of hypoxia and its variability, history, and dynamics.

Low oxygen values are of concern because of detrimental effects to marine life, biodiversity, commercial and recreational fisheries, and ecosystem functioning (Rabalais and Turner, 2001). Demersal fishes, crabs, and shrimp will attempt to move away from oxygen concentrations less than 2 mg l^{-1} , and few marine animals survive in prolonged exposure to oxygen concentrations below that level. Thus, the hypoxic area is popularly known as the “Dead Zone.”

The Mississippi River forms the largest watershed on the North American continent (Figure 1), with an annual average discharge of 580 cubic kilometers (km^3) into the northern Gulf of Mexico through two main distributaries: the birdfoot delta southeast of the City of New Orleans, Louisiana, and the Atchafalaya River delta

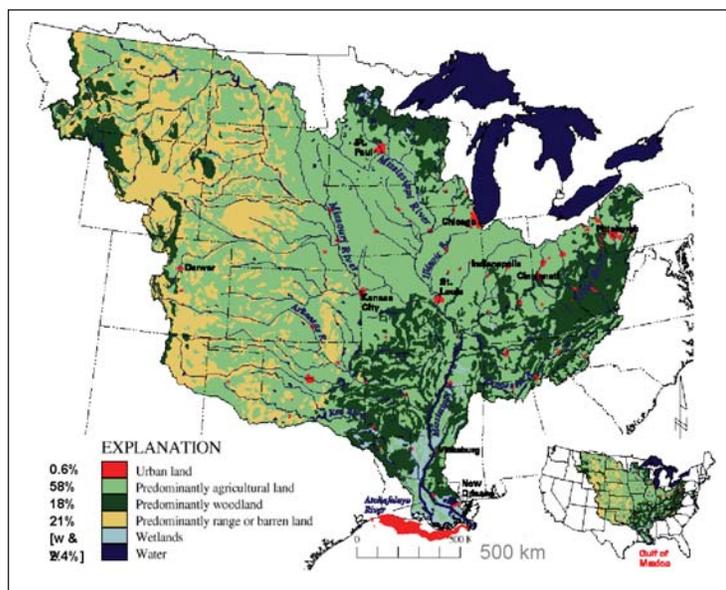


Figure 1. Mississippi River watershed and land use (Goolsby et al., 1999) with the 2002 area of Gulf of Mexico hypoxia superimposed (Rabalais, 2002).

200 km to the west (Meade, 1995). The Mississippi and Atchafalaya Rivers are the primary sources of freshwater, nitrogen, and phosphorus to the northern Gulf of Mexico, delivering 80 percent of the freshwater inflow, 91 percent of the estimated annual nitrogen load, and 88 percent of the phosphorus load (Dunn, 1996).

Freshwater, sediments, and dissolved and particulate materials are carried predominantly westward along the Louisiana/Texas inner to mid-continental shelf, especially during peak spring discharge (Rabalais et al., 1996; Smith and Jacobs, 2005). 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 freshwater all suggest that the shelf receiving the freshwater behaves as an "unbounded" estuary stratified for much of the year (Dinnel and Wiseman, 1986). The stratification is due primarily to salinity differences, and the stratification intensifies in the summer with the warming of surface waters (Wiseman et al., 1997). The primary pycnocline depth varies seasonally with discharge and physical mixing

from 3 to 5 meters (m) to 10 to 15 m in a 20-m water column (Rabalais and Turner, 2001; Rabalais et al., 2002c).

Seasonal hypoxia of bottom waters in this region is the result of strong and persistent stratification coupled with the high organic production in overlying surface waters that is fueled by river-derived nutrients (Figure 2) (CENR, 2000; SAB, 2008).

The nutrients delivered from the Mississippi River Basin support the primary productivity within the immediate vicinity of the river discharges, as well as across the broader Louisiana and upper Texas continental shelf. The flux of fixed carbon in the form of senescent phytoplankton, zooplankton fecal pellets, or aggregates to the lower water column and seabed provides a large carbon source for decomposition by aerobic bacteria. The decay process consumes dissolved oxygen in the water column at a higher rate than resupply from the upper water column in a stratified water column, leading to hypoxia in large portions of the lower water column for months at a time from the spring to the fall (Rabalais and Turner, 2001; Rabalais et al., 2002 a,b).

Hypoxia, as a symptom of eutrophication, is a growing problem around the world (Diaz and Rosenberg, 1995, in press; Boesch, 2002). Eutrophication is the increase in the rate of production of carbon or the accumulation of carbon in an aquatic ecosystem (modified from Nixon, 1995). While the causes may include direct natural or anthropogenic carbon enrichment, eutrophication in the coastal ocean and in the twentieth and twenty-first centuries is

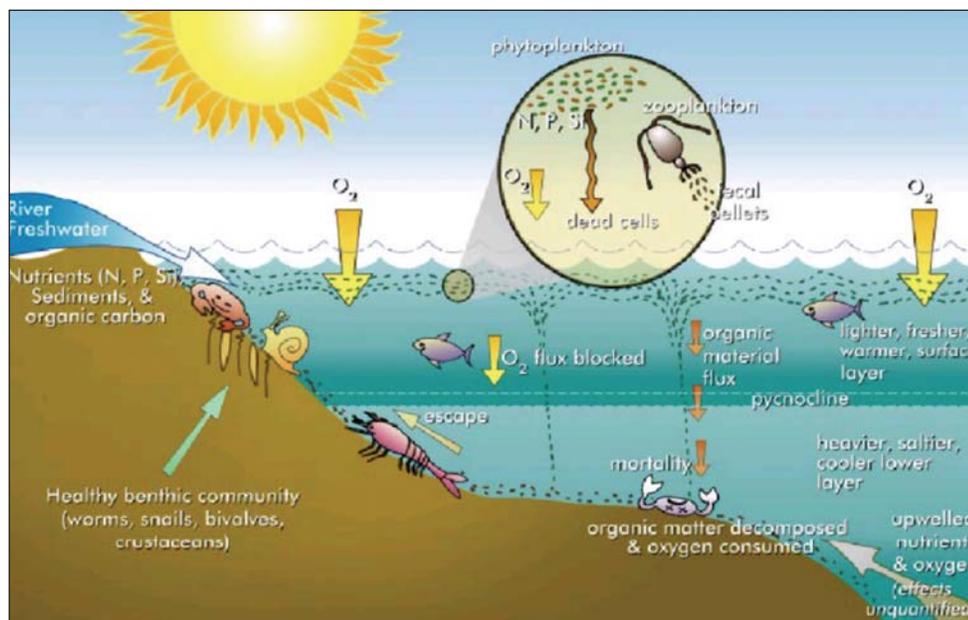


Figure 2. Physical and biological processes that support the formation and maintenance of hypoxia on the Louisiana shelf (CENR, 2002).

more often caused by excess nutrients that would otherwise limit the growth of phytoplankton. The extent and persistence of hypoxia on the Louisiana/Texas shelf makes the Gulf of Mexico “Dead Zone” the second largest human-caused hypoxic zone globally and a “poster child” for deteriorating coastal water quality and the need for nutrient management.

Dimensions and Variability of Hypoxia

The extent of hypoxia primarily in July averaged 13,500 km² from 1985 to 2007, with a range from negligible in 1988 (a summer drought year for the Mississippi River basin) to 22,000 km² in 2002 (2007 depicted in Figure 3).

The size of the area is most closely related to the amount of nitrate-nitrogen delivered by the Mississippi River in the spring (Turner et al., 2005, 2006, 2008). The midsummer hypoxic water mass is distributed across the Louisiana shelf west of the Mississippi River and onto the upper Texas coast (Rabalais and Turner, 2001; Rabalais et al., 2002a). Hypoxia extends from near shore to as much as 125-km offshore and in water depths extending from the shore in 4- to 5-m up to 60-m deep. Midsummer hypoxia usually extends along a single continuous zone, but may occur in distinct areas west of the Mississippi and Atchafalaya River deltas. Hypoxia reaches onto the upper Texas coast as far as Freeport, Texas (~95°20'W, 10- to 20-m water depth), during periods of high discharge and delayed return of currents from the west (Pokryfki and Randall, 1997; Harper et al., 1981, 1991; Rabalais et al., 1999, unpublished data). Variations in the distribution are caused by the prevailing oceanographic conditions (e.g., 1998 when persistent currents from the west constrained the hypoxic region to a more

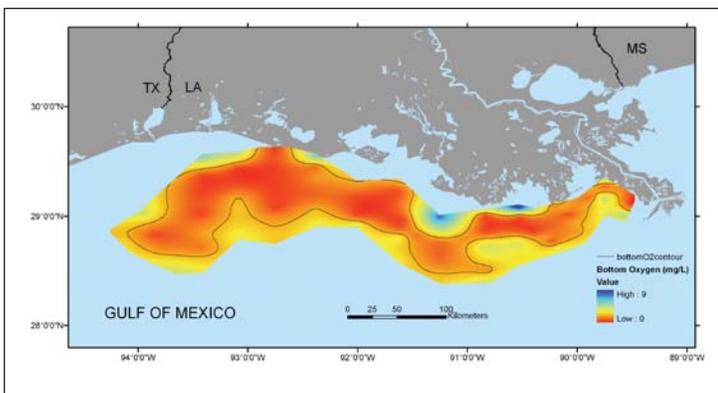


Figure 3. The distribution of bottom-water hypoxia in mid-summer 2007. The black line indicates the area of bottom-water with dissolved oxygen levels less than 2 mg l⁻¹.

easterly location) or disruption of stratification and reaeration by tropical storms and hurricanes.

The 2003 and 2005 summer distributions of hypoxia (Figure 4) were affected by a series of storms. Within 2 weeks prior to the mapping cruise, Hurricane Claudette in July 2003 generated 3- to 4-m waves and mixed the water column, disrupting hypoxia that did not reform completely until after the “official” size determination. The predicted area of 18,000 km² was reduced to 8,600 km² in 2003.

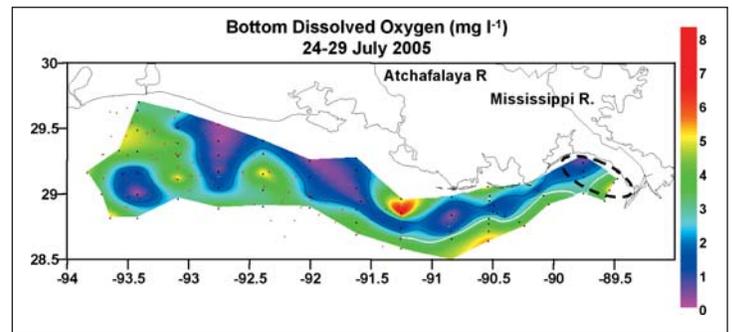


Figure 4. Distribution of mid-summer bottom-water hypoxia in 2005 following Hurricanes Cindy and Dennis, but prior to Hurricanes Katrina and Rita. The area outlined with a dashed line indicates the distribution of bottom-water hypoxia 2 weeks post-Hurricane Katrina.

In early July 2005, there was a large area of hypoxia off the southwestern Louisiana coast. Before the late July mapping of hypoxia, Hurricanes Cindy and Dennis affected the Louisiana shelf. The late July distribution was less than predicted (Turner et al., 2005, 2006), but the hypoxia was still fairly well formed on the southwestern shelf. Hurricane Katrina made landfall at the end of August and disrupted hypoxia in depths less than 25 m, but it reformed in the shallow waters of the Louisiana Bight a few weeks later. A series of frontal passages and Hurricane Rita in September 2005 dissipated the hypoxia for the remainder of the year.

More frequent sampling on the southeastern Louisiana coast off Terrebonne Bay 100-km west of the Mississippi River delta indicates that hypoxia occurs from as early as late February through early October and nearly continuously from mid-May through mid-September (Rabalais et al., 1999, 2002a). Hypoxia is rare in late fall and winter. A detailed time series of oxygen conditions is available from oxygen meters deployed at observing systems. A “typical” year is shown in Figure 5.

Strong mixing events are associated with cold fronts in spring and fall and tropical storms and hurricanes in summer that result in an increase in bottom-water oxygen levels from near anoxic to

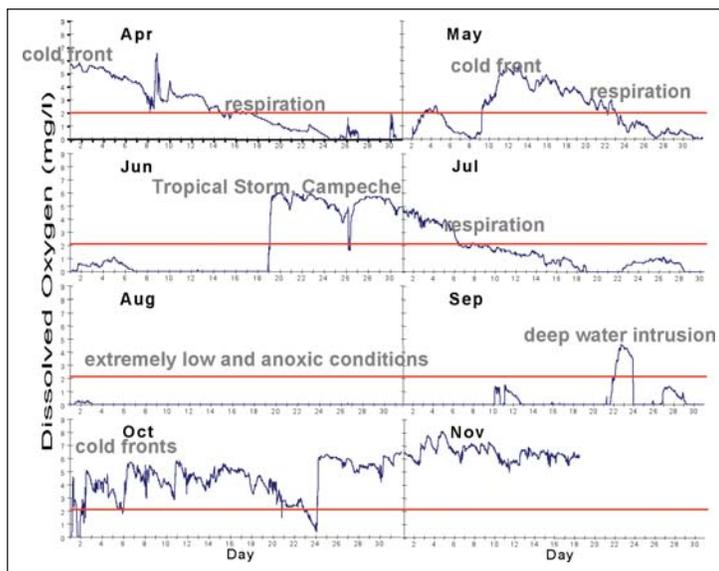


Figure 5. Continuous bottom-water oxygen concentration at 20-m depth in an area with frequent hypoxia in 1993 (taken from Rabalais et al., 2002a).

above 6 mg l⁻¹. Following a mixing event and reoxygenation of bottom waters, a gradual decline of bottom oxygen concentrations driven by aerobic respiration of organic matter recommences and continues as long as the stratification is maintained. Stratification persists as long as mixing does not occur, and periods of oxygen concentrations less than 1 mg l⁻¹ or near anoxia last from one-half to 2 months in May-September. Short-lived increases in bottom-water oxygen during the summer are usually the result of intrusions of higher oxygen content water from depth during upwelling-favorable wind conditions, followed by a relaxation of the winds and movement of the low oxygen water mass offshore.

Mississippi River Discharge and Nutrient Loads

Because the amount of freshwater delivered to the northern Gulf of Mexico influences both the nutrient loads and the strength of salinity stratification on the shelf, variability or long-term trends in river discharge will influence the extent and severity of hypoxia.

Depending on the period of record analyzed, there are – or are not – long-term trends in the discharge of the Mississippi River. Interannual variability in discharge is high, but the 1820-1992 average (multi-decadal time scale) for the Mississippi River at Vicksburg has been relatively stable near 17,000 cubic meters per second (m³ s⁻¹) (Turner and Rabalais, 2003; Turner et al., 2007). Karl and Knight (1998) reported an increase in precipitation by

about 10-percent across the contiguous United States between 1910 and 1997, including parts of the Mississippi River basin. On the other hand, a high-temporal resolution, 100-year data set from the Mississippi River coupled with sub-watershed and precipitation data indicate an increase in discharge from agricultural watersheds that is clearly anthropogenically driven and that has not been balanced by a rise in precipitation. This finding is relevant to nutrient fluxes to the Gulf of Mexico.

Nitrate load from the Mississippi River increased about 300 percent from the 1950s to the mid 1990s (Goolsby et al., 1999; Goolsby and Battaglin, 2001), whereas stream flow from the basin increased only 30 percent (Bratkovich et al., 1994). The most significant driver in the change in nitrate load is the increase in nitrate river concentration, not freshwater discharge (Justić et al., 2002; Turner et al., 2008). Using two different approaches, Donner et al. (2002) and Justić et al. (2003) both concluded that only 20 to 25 percent of the increased nitrate load between the mid-1960s to the mid-1990s was attributable to greater runoff and river discharge, with the rest due to increased nitrogen concentrations in the lower river.

Nonetheless, with nitrate concentrations in the lower Mississippi River remaining near 100 micromolar (µM) since the early 1990s (Figure 6) (Turner et al., 1998, 2007), climate-driven changes in discharge are likely to have a significant influence on the seasonal formation of and interannual variability in hypoxia in contrast to the period between 1970 to 1990, when nitrate concentrations were rapidly increasing. Similar results by Donner and Scavia (2007) indicate that climate variability could now be

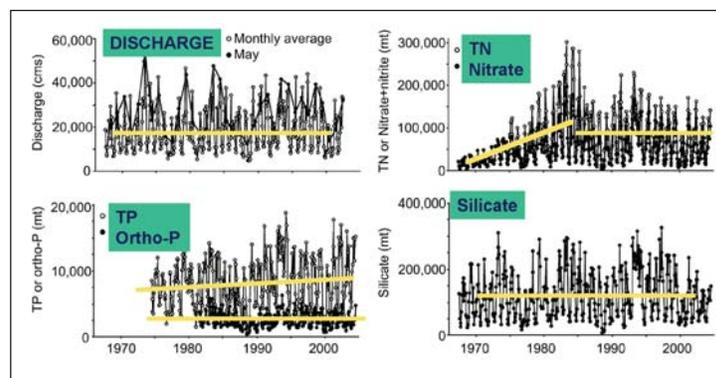


Figure 6. The monthly discharge (cubic meters per second) and nutrient loads of total phosphorus (TP), total nitrogen (TN), nitrate, and dissolved silicate in metric tons (mt) flowing down the main channel of the Mississippi River and into the Gulf of Mexico from 1968 to 2004. From Turner et al. (2006).

controlling the variability in nitrogen leaching from land and transport to the Gulf of Mexico.

The overall driver of the nitrogen load from the Mississippi River over the long-term, when changes in the coastal ecosystem became evident, is due to changes in nitrate concentration (Goolsby and Battaglin, 2001; Turner et al., 2007, 2008). The concentrations of nitrate-nitrogen in the Mississippi River (2007 to 2008) are at the upper limit for the long-term average (Figure 7) (Turner et al., 2008, unpublished data). There is clearly more nitrate-nitrogen per volume of Mississippi River discharge presently than in the past.

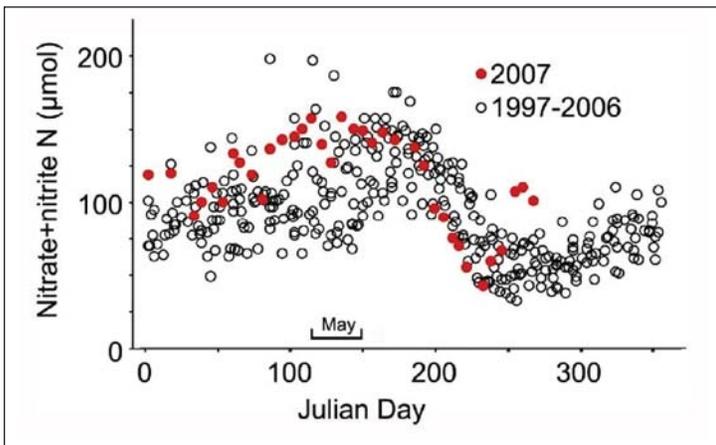


Figure 7. Concentration of nitrate + nitrite nitrogen in the Mississippi River at Baton Rouge, Louisiana, from 1997 through 2006 and during 2007. There were more than 15-million new acres of farmland devoted to corn in 2007 than in 2006. From Turner et al. (2008).

There are no regular and reliable records of total phosphorus concentrations in the lower Mississippi River before 1973, and subsequent values vary greatly among years. There is a slight upward trend in total phosphorus, but ortho-phosphate concentrations remain level since the early 1980s. Over similar periods, the concentration of silicate decreased anywhere from 30 to 50 percent depending on the period of record, but the load remains similar. The limitation of phytoplankton growth by silica has implications for the types of phytoplankton in the community, fluxed carbon in the form of diatoms, trophic interactions, and the formation of hypoxia.

An important management issue is the relative influence of nitrogen versus phosphorus concentrations and loads in controlling bottom-water dissolved oxygen on the Louisiana continental shelf. Model results indicated a general tendency for responses to nitrogen load reductions to be somewhat greater than for phosphorus load reductions (Limno-Tech, Inc., 1995). Both phosphorus and silica may also be limiting at times and in certain locations, or

combinations of nutrients may be limiting (Rabalais et al., 1999, 2002b; CENR, 2000; Sylvan et al., 2006; SAB, 2008).

A model by Turner et al. (2006) discerned the relative strengths of the loading of various forms of nitrogen, phosphorus, dissolved silicate, and their molar ratios on the variance in the size of the summertime low oxygen zone. A stable multiple regression that included as variables Year and river nitrate + nitrite loading for the 2 months prior to the measurement of the hypoxic zone described 82 percent of variation in the size of the hypoxic zone from 1978 to 2004 (Figure 8).

The inclusion of the time variable Year is consistent with the documented increase in carbon stored in sediments, as indicated by diatom remains in the form of biogenic silica, after the 1970s (Rabalais et al., 2004; Turner et al., 2004, 2008). The variable Year is negatively correlated with the total nitrogen to total phosphorus (TN:TP) ratio (currently fluctuating around 20:1) in a way that suggests nitrogen – not phosphorus – has become more important as a factor limiting phytoplankton growth in the last 20 years. Hindcasting this relationship also lends credence to the historical sediment record that hypoxia was limited in extent in the early 1970s. Nitrogen (specifically, nitrate + nitrite) appears to be the major driving factor influencing the size of the hypoxic zone on this shelf, but phosphorus is also related. Thus, both nitrogen and phosphorus management have implications for reducing hypoxia.

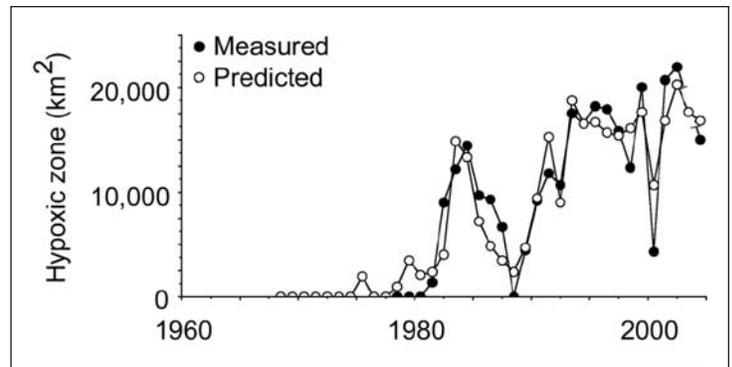


Figure 8. The results of a final model predicting the size of the hypoxic zone from 1968 to 2004, and the estimates over the whole shelf. The equation is: $Y \text{ (km}^2\text{)} = -1337953.4 + 672.1589 * \text{Year} + 0.0998 * (\text{May flux as NO}_{3+2}\text{)}$. The hindcast values plotted as zero prior to 1978 are negative values in the model. Similar analyses with discharge, phosphates (PO_4), total phosphorus (TP), total nitrogen (TN), silicon (Si), and various Si:N:P ratios indicate that nitrogen (N), in the form of NO_3+NO_2 , is the major driving factor influencing the size of hypoxia on the Louisiana shelf. From Turner et al. (2006).

Long-Term Trends in Hypoxia

Because there were no comprehensive, direct measurements of dissolved oxygen in the region prior to the 1980s, indirect evidence of the intensification of hypoxia from the sediment record provides support for the conclusion that regularly occurring and widespread hypoxia became a common feature of the northern Gulf shelf only after nutrient loading increased during the last half of the twentieth century.

Indicators of increased biological production and decreased oxygen availability in the sediment record provide information to support the conclusion that hypoxia has intensified in the last half of the twentieth century as a result of increased nutrient loading (Rabalais et al., 1996, 2002a, 2007). These indicators include increased accumulation of organic matter and biogenic silica in sediment deposits (reflecting increased primary production and diatom production) and increased glauconite (a mineral indicative of reducing environments) as a percentage of coarse-grained sediments, decreased diversity of ostracods and benthic foraminiferans, and changes in the species composition of benthic foraminiferans (all indicative of depleted oxygen conditions).

These trends show that, while there are signs of increased production and oxygen depletion earlier in the twentieth century, the most dramatic changes have occurred since the 1960s, when the rise in the nitrate concentration and loads in the Mississippi River began. In other words, hypoxia as a widespread phenomenon on the Louisiana shelf is not natural. The long-term data on hypoxia, sources of nutrients, associated biological parameters, and paleoindicators continue to verify and strengthen the relationship between the nitrate-N load of the Mississippi River, the extent of hypoxia, and changes in the coastal ecosystem (eutrophication and worsening hypoxia) that reflect the increased nitrogen loads.

Coherence with Other Hypoxic Areas

Several global syntheses of hypoxia and eutrophication have been published. Diaz and Rosenberg (in press) updated their previous synthesis (1995) on marine benthic hypoxia and increased, once again, the number of documented coastal areas of hypoxia and worsening hypoxia. Cloern (2001) published a conceptual model of coastal eutrophication along with many examples. Rabalais (2004) presented many examples of increased nutrient loading (nitrogen and phosphorus), increased primary production,

loss of macrovegetation, increased incidence of harmful algal blooms, and increased hypoxia in several coastal ocean systems since 1960. Boesch (2002) added to Cloern's inventory and bracketed when the changes in these eutrophying coastal ecosystems began.

In almost all cases, the "tipping points" fell within a 20-year period between 1960 and 1980, a period during which there was a dramatic increase in the amount of fixed nitrogen being added to the biosphere, mainly from industrially fixed fertilizers (Galloway and Cowling, 2003). The same tipping point for Gulf of Mexico hypoxia falls within that timeframe (Turner et al., 2008).

Sources of Nutrients

While it was not a simple and straightforward path to identify the changes in land use and nutrient loads that led to the formation and historical worsening of Gulf of Mexico hypoxia, the scientific evidence is much clearer than a path to correcting the problem. Fingers point in multiple directions and heads duck, but that is not the appropriate way to address the problem.

Several careful budgets accounting for nutrient inputs, yields, and loads for the Mississippi River watershed and its sub-basins have been developed (Downing et al., 1999; Goolsby et al., 1999; Turner et al., 2004; Alexander et al., 2008), along with multiple methods and suggestions for reducing nutrient inputs (CENR, 2000; Mitsch et al., 1999, 2001; SAB, 2008). The way to address nutrient overloads to coastal systems is to identify the sources, locations, source activities, and amounts reaching the estuaries and nearshore waters and to develop nutrient management strategies that effectively and efficiently address the most culpable sources (National Research Council, 2000; SAB, 2008).

Watersheds differ in the sources and amounts of nutrient loads. An urbanized estuary, such as Long Island Sound, receives most of its nitrogen and phosphorus overload from wastewater treatment plants in New York City and the Connecticut coastal zone. Chesapeake Bay receives equivalent inputs of nitrogen from atmospheric deposition, agricultural nonpoint sources, and urbanized impervious surfaces and wastewater. Phosphorus loads to the Chesapeake Bay are split among agricultural nonpoint sources and urban wastewater.

The Mississippi River watershed, on other hand, is primarily an agricultural landscape (approximately 60 percent) with some forests and rangeland, but limited point sources of nitrogen and phosphorus from urban and industrial activities and limited atmospheric deposition.

The most current analysis of sources of nutrient loads from the Mississippi River watershed are in Alexander et al. (2008), who used the SPARROW water quality model. Their results indicate that agricultural sources in the watershed contribute more than 70 percent of the delivered nitrogen and phosphorus (Figure 9).

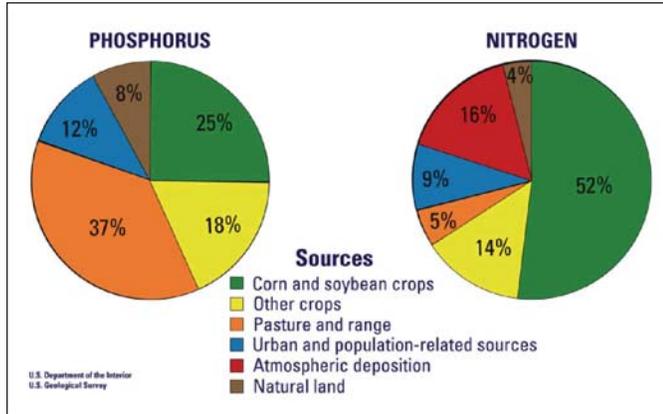


Figure 9. Percent contribution of various sources of nitrogen and phosphorus from the Mississippi River watershed to the Gulf of Mexico (http://water.usgs.gov/nawqa/sparrow/gulf_findings/).

Corn and soybean crop rotations are the largest contributor of nitrogen (52 percent), followed by atmospheric deposition (16 percent). For phosphorus sources, animal manure on pasture and rangelands is the primary source (37 percent), followed by corn and soybean rotations (25 percent), other crops (18 percent), and urban sources (12 percent). This work confirmed earlier results (Alexander et al., 2000) that the fraction of in-stream nitrogen (and now phosphorus) delivered to the Gulf of Mexico increases with stream size. Reservoir trapping of phosphorus, however, can cause large local- and regional-scale differences in delivery. These results also confirmed earlier estimates of relative contributions of nitrogen sources and their change over time (Figure 10).

The work of Alexander et al. (2008) also confirmed earlier reports of the sub-basins responsible for most of the nitrogen and phosphorus loads in the Mississippi River watershed (Goolsby et al., 1999; Turner et al., 2004), but in a much more detailed, smaller watershed approach (Figure 11).

Much of the nitrogen and phosphorus delivered to the Gulf originates from generally similar regions and watersheds of the Mississippi-Atchafalaya River Basin. These include many watersheds in the Central Mississippi, Ohio, and Lower Mississippi regions, areas that have the highest delivered nutrient yields. The lowest delivered nutrient yields are observed for watersheds in the western regions

of the Mississippi River watershed, where nutrient source inputs are generally smaller and the lower streamflows and longer river distances enhance in-stream nutrient removal. In further analyses, Alexander et al. (2008) attributed the majority of the nutrient loads from nine states – Iowa, Illinois, Indiana, Missouri, Ohio, Kentucky, Tennessee, Arkansas, and Mississippi – denoted the “Nutrient Nine” by the *Times-Picayune* newspaper in New Orleans, Louisiana, on February 1, 2008.

How to Accomplish Nutrient Management

The history of the development of understanding the linked river-ocean system and the changes in loads and sources of nutrients were interwoven along the way with the development of a science-based resource management strategy (Figure 12) (Rabalais et al., 2002a).

With the causes of hypoxia more clearly defined and the sources of nutrients fairly well understood, the next step was the development of an overall nutrient strategy. The implementation of a science-based resource management policy remains a daunting task for a watershed covering 41 percent of the contiguous United States, 31 states, and numerous legislative, political, institutional, and societal entities (National Research Council, 2007).

While there was conjecture by the mid-1970s that a significant area of hypoxia existed on the Louisiana shelf, the first shelfwide cruise in 1985 confirmed its enormous size. As additional research in the early 1990s pointed to its connection to the Mississippi-Atchafalaya system, there were repeated attempts from academic

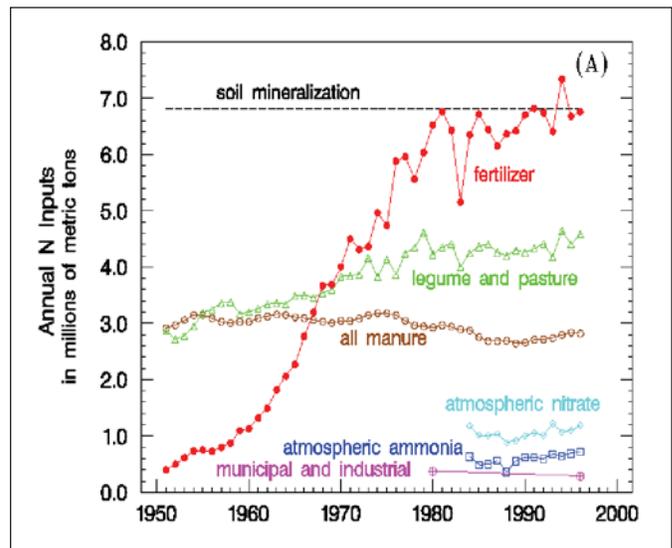


Figure 10. Annual nitrogen inputs to the Mississippi-Atchafalaya River Basin (1951 to 96). From Goolsby et al. (1999).

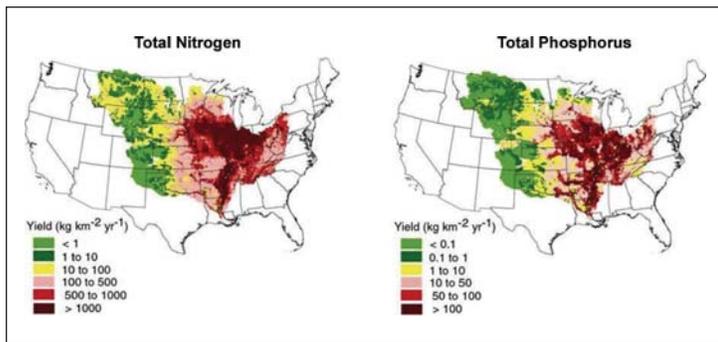


Figure 11. Total nutrient yield delivered to the Gulf of Mexico from sources in the incremental drainages of the Mississippi-Atchafalaya River Basin reaches for total nitrogen and total phosphorus. From Alexander et al. (2008) and http://water.usgs.gov/nawqa/sparrow/gulf_findings/.

and federal scientists to bring this issue to the attention of managers and policy makers. Supporting these attempts was a solid basis of peer-reviewed and published research papers, and they helped lay a solid scientific foundation for dialog among policy makers.

Public stakeholders most effectively brought this scientific knowledge to the attention of managers and policy makers and created the final impetus for action. Releasing annual maps of the extent of the hypoxic zone, beginning in 1993, captured the attention of the press and then the public, including non-governmental stakeholders. In 1995, a group of 17 stakeholder groups led by the Sierra Club Legal Defense Fund (now the Earth Justice Legal Defense Fund) petitioned officials of the EPA and the state of Louisiana to convene a general management conference under section 319(g) of the Clean Water Act. The EPA's response, along with other agencies, was to initiate an exchange of scientific knowledge and public information through a series of workshops and symposia. Louisiana also decided not to petition for the interstate management conference. The stakeholders' petition, however, did raise the attention of managers and policy makers.

A series of conferences beginning in 1995 and 1996 in New Orleans, Louisiana, and Davenport, Iowa, conveyed information on the dynamics and effects of hypoxia, links to nutrient loads from the Mississippi River system, and management activities underway in the basin. Soon after, the EPA convened meetings of high-ranking federal principals to start the policy dialog and asked the White House Office of Science and Technology Policy to conduct an Integrated Assessment of the Causes and Consequences of Hypoxia in the Northern Gulf of Mexico. In December 1997, the

federal group was expanded to include state and tribal officials, and the combined federal, state, and tribal Task Force met for the first time and, subsequently, six other times through 2000 to develop the Action Plan. While many sources informed the Action Plan, the Integrated Assessment (CENR, 2000) became the centerpiece of scientific input because it was:

- Responsive to the policy-relevant questions.
- Broadly integrative and synthetic.
- Based on high-quality monitoring data.
- Predictive.
- Based on peer review and public participation.

The Integrated Assessment process convened six teams of scientific experts who synthesized decades of research and monitoring on:

- The extent, characteristics, causes, and effects (both ecological and economic) of Gulf hypoxia.
- Flux and sources of nutrients in the Mississippi River system.
- Effects of reducing nutrient loads on waters within the basin and in the Gulf.
- Methods to reduce nutrient loads.
- Social and economic costs and benefits of methods to reduce nutrient loads.

The six technical reports, with a cumulative authorship of 47 scientists, were peer reviewed under the guidance of an

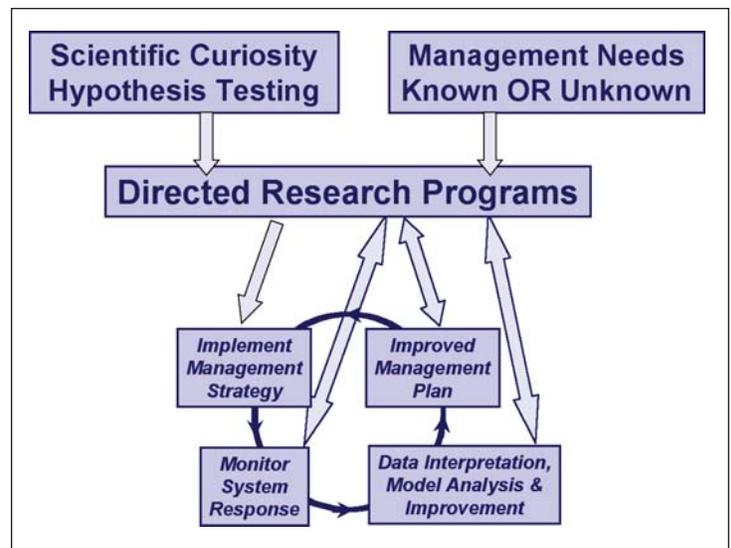


Figure 12. Conceptual flow chart of observations, hypothesis testing, and research results that lead to management strategies with their subsequent modification based on ecosystem responses and modified management. The course of events is never fully realized.

independent editorial board composed of highly-respected scientists who were approved by both the assessment team and the Task Force. After peer review, the six reports were released for formal public comment, generating many hundreds of pages of input. Those comments and the six reports formed the basis of the Integrated Assessment, which was also released for public comment before finalizing. While the Integrated Assessment was clearly policy-relevant in its initiation, it became more so when, in 1998, the Congress passed and the President signed into law the Harmful Algal Bloom and Hypoxia Research and Control Act (P.L. 105-383), which codified its development and established a formal Task Force to deliver an Action Plan (Figure 13).

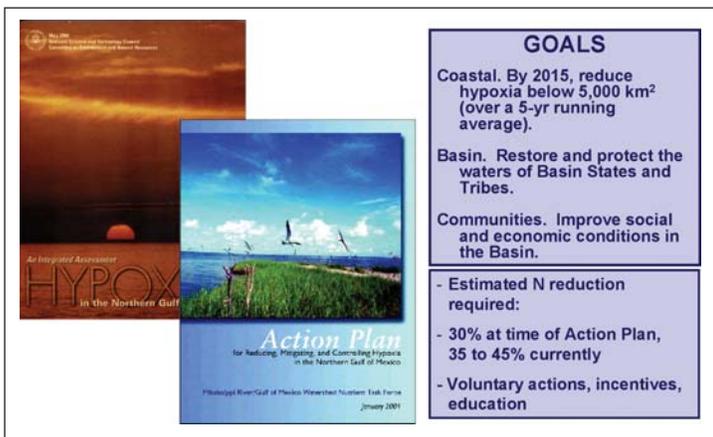


Figure 13. The documents intended to identify and implement mechanisms to reduce nutrient loads to the Gulf of Mexico and reduce the size of the “Dead Zone.”

Reaching consensus on the Integrated Assessment and Action Plan was not without controversy or debate. Dialog 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, which provided a forum for exchange between the Task Force, participants in the scientific assessment, and a range of stakeholders on issues related to the science, views on action strategies, and implications for various groups of 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 Action Plan was made available for public comment prior to the final meeting of the Task Force in October 2000. At

that final meeting, a unanimous consensus was reached to take steps to improve water quality within the Mississippi River basin and the northern Gulf of Mexico. The Action Plan was cleared by the state, tribal, and federal agencies and delivered by the President to Congress in early January 2001 prior to a change in administrations (see Figure 12). Fortunately, the EPA Administrator early in President Bush’s administration, Christine Todd Whitman, was able to re-instate the Task Force and continue the dialog for improved water quality within the Mississippi River watershed and the Gulf of Mexico. Perhaps she, as the former Governor of New Jersey, was distressed that so many size comparisons of the midsummer hypoxia were equated to the size of the State of New Jersey!

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

Table 1. Approaches for Controlling Nitrogen in the Mississippi River Basin

<p>On-site control of agricultural drainage</p> <ul style="list-style-type: none"> Changing cropping systems Reducing nitrogen fertilizer application rates Managing manure spreading Managing the timing of nitrogen application Using nitrification inhibitors Changing tillage methods Increasing drainage tile spacing
<p>Off-site control of agricultural drainage</p> <ul style="list-style-type: none"> Wetlands Riparian zones
<p>Urban and suburban nonpoint source control</p>
<p>Point source control</p> <ul style="list-style-type: none"> Environmental technology Ecotechnology
<p>Control of atmospheric NOx</p>
<p>Mississippi River diversions</p>
<p>Upper Mississippi River flood control and restoration</p>

From Mitsch et al. (2001).

wanted voluntary, incentive-based actions. The compromise included a quantitative environmental goal for the Gulf, consistent with historical data and model predictions, recognition that a 30-percent nitrogen load reduction was likely needed to reach that goal, and an implementation approach based primarily on voluntary, incentive-based sub-basin strategies. Since the completion of the Action Plan, it is apparent that nitrogen load reductions closer to 35 to 45 percent would be necessary to reduce the size of the midsummer hypoxia (Scavia et al., 2003; Justić et al., 2003).

Nutrient Reduction Strategies

Nutrient reduction strategies, as identified in the Action Plan, would include agricultural best management practices, wetland restoration and creation, river hydrology remediation, riparian buffer

strips, and stormwater and wastewater nutrient removal (Mitsch et al., 1999, 2001). The various approaches are outlined in Table 1.

Not all methods for reducing nutrients are as effective as others (Table 2, Figure 14). There are also economic considerations with the initial and capitalized cost of the nutrient reduction strategies (Doering et al., 1999).

For instance, more nitrogen can be removed from the system with modified agricultural management than with restored wetlands or use of riparian buffer strips. The cost of some of the agricultural management schemes, however, may be initially cost-effective but, in the long-term, may continue to be a constant cost factor. McIsaac et al. (2001, 2002) predicted that a 12- to 14-percent decrease in the application of fertilizer in the Mississippi River basin could reduce the net anthropogenic nitrogen inputs by

Table 2. Recommended Approaches for the Reduction of Significant Amounts of Nitrogen Loading to Streams and Rivers in the Mississippi River Basin and Gulf of Mexico

Approach	Potential Nitrogen Reduction ¹ (10 ³ metric tons per yr)
Changing farm practices	
Nitrogen management: Reduction in “insurance” rates of nitrogen fertilizer application, proper distribution of manure, application of appropriate credits for previous crop legumes and manure, and application of improved soil nitrogen testing methods.	900–1400
Alternative cropping systems:	500
Perennial crops substituted for 10% of the present corn–soybean area.	
Improved management of animal manure in livestock-producing areas	500
Minimum spacing of 15 m between farm drainage tiles	?
Creating and restoring wetlands and riparian buffers	
Create or restore 21,000–53,000 km ² (5–13 million acres) of wetlands in the Mississippi River Basin (0.7% to 1.8% of the Basin).	300–800
Restore 78,000–200,000 km ² (19–48 million acres) of riparian bottomland hardwood forest (2.7% to 6.6% of the Basin).	300–800
Reducing point sources	
Tertiary treatment of domestic wastewater.	20
Flood control in the Mississippi	
River diversions in the delta.	50–100

From Mitsch et al. (2001).

¹Estimated on-site source reductions do not translate to equivalent reductions in Gulf of Mexico nitrogen loading, because only about 8 percent of nitrogen sources reach the lower Mississippi River.

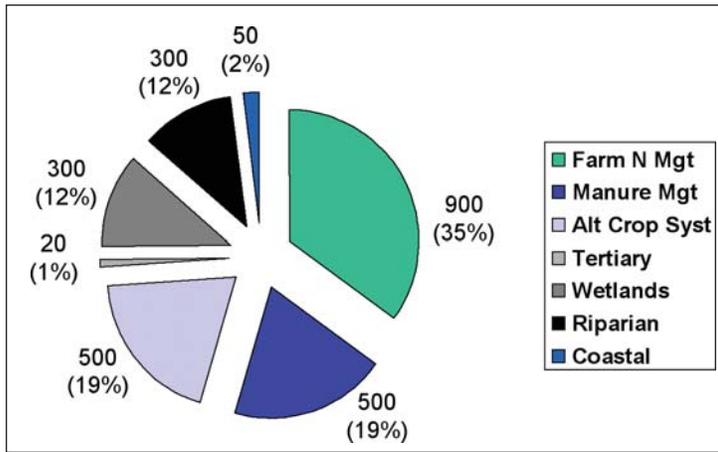


Figure 14. Relative proportion of the nitrogen load to be removed by various nutrient management strategies within the Mississippi River watershed (drawn from data in Mitsch et al., 1999, 2001).

30 percent without a reduction in crop production. On the other hand, the creation of artificial wetlands, while initially expensive, will become more cost-effective the longer they are in place. Tertiary treatment of wastewater is an expensive proposition and also reduces little of the overall load of nitrogen to the Gulf of Mexico. In cities such as Des Moines, Iowa, and Columbus, Ohio, tertiary treatment is necessary, especially in the spring, when nitrate concentrations exceed drinking water standards.

As mentioned, however, the range of cost effectiveness of various measures is quite broad (Table 3) and should help guide nutrient reduction strategies.

Clearly, knowing what nutrient management strategies, as outlined above, and advanced technologies (*sensu* the Clark Prize lecture of Dr. James L. Barnard in 2007) does not necessarily equate to “action” as defined in the 2001 Action Plan. In fact, the 2001 Action Plan and its revised version in 2008 are often called “Inaction Plans” for their lack of commitment of resources to make a difference and the dependence entirely upon voluntary, incentive actions.

Current Policy Status

A necessary component of the Action Plan (2001) was the idea of adaptive management, whereby new research results, modeling efforts, and findings from experimental or watershed-level experiments would feed back into an improved Action Plan.

Within 5 years of the initiation of the Action Plan (2001), there was a call for a reassessment of the science basis, modeling improvements and their outcomes, and management

accomplishments and a revised Action Plan. This process began in 2006 with a series of conferences and white papers destined for peer-reviewed science publication.

The EPA Science Advisory Board (SAB) convened a Hypoxia Assessment Panel (HAP) that reviewed the science background, newer information on nutrient loads and sources, and a better detailed analysis of agricultural practices and economics within the Mississippi River watershed. Parallel to this effort, the federal-state Task Force began the formulation of a new Action Plan. The work of the SAB/HAP was completed in 2007 (Figure 15), and the new Action Plan was signed into effect in June 2008 at The Historic New Orleans Collection, Royal Street Complex, Counting House.

The SAB report supported and strengthened the science supporting nutrient management within the Mississippi River watershed to improve water quality both within the watershed and in the receiving waters of the northern Gulf of Mexico. The SAB report reiterated that:

- Nitrogen loading drives the timing and extent of hypoxia.
- Phosphorus loads are also significant in the watershed and affect Gulf of Mexico hypoxia.
- The HAP recommends a dual nitrogen and phosphorus reduction strategy.

Table 3. Cost Effectiveness of Nutrient Reduction Strategies for the Mississippi River Watershed

Method	Unit Cost (\$/kg)
Edge of field losses	
20%	0.88
40%	3.37
Reduce fertilizer use	
20%	0.69
45%	2.85
Wetlands	
1 M acres	6.06
5 M acres	8.90
Riparian buffers	
19 M acres	26.03
Coastal diversions	~6
Tertiary treatment	~40

From Doering et al. (1999).

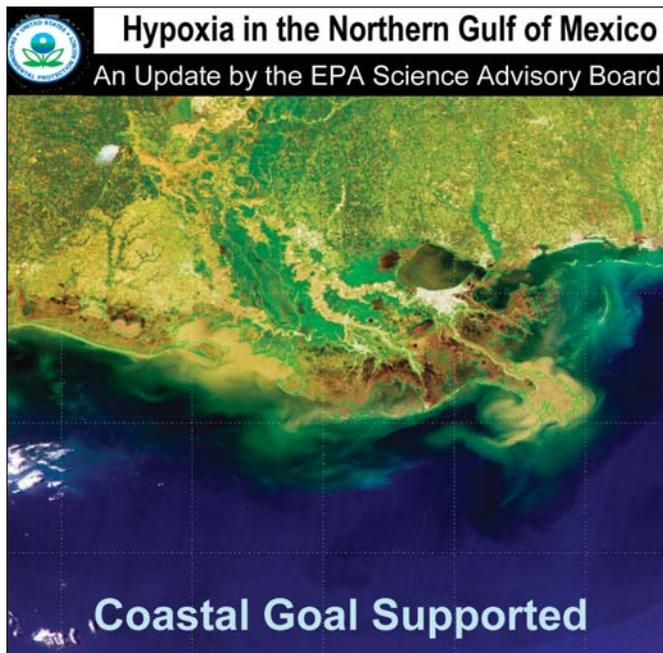


Figure 15. The SAB (2008) report stated that plans should be initiated to ... “strive to reduce or make significant progress towards reducing the 5-year running average areal extent of the Gulf of Mexico hypoxic zone to less than 5,000 km² by the year 2015 through implementation of specific, practical, and cost-effective voluntary actions by all Federal agencies, States, and Tribes, and address all categories of sources and removals within the Mississippi/Atchafalaya River Basin to reduce the annual discharge of nitrogen and phosphorus into the Gulf.”

- ▶ The Upper Mississippi River and the Ohio River contribute 84 percent of the nitrate-N and 64 percent of the phosphorus eventually reaching the Gulf of Mexico.
- ▶ Tile-drained, corn-soybean landscapes are very nitrogen “leaky.”
- ▶ Management scenarios should target the tile-drained Corn Belt region of the Mississippi River watershed for nitrogen and phosphorus reductions in both surface and sub-surface waters.

The new plan sticks to the 2001 goal of 5,000 km² by 2015, but drafters of the plan acknowledge that it might already be too late to reach that goal with the limited action to date and visible in the near future. The revised Action Plan calls for states to devise solutions “as soon as possible, but no later than 2013.” That is, “If states wait until 2013, though, that means they would have to deliver results in just 2 years, which is an unrealistic and probably meaningless timetable” (*Times-Picayune*, New Orleans,

Louisiana, February 27, 2008).

A diversity of management approaches are required to achieve efficient control of nutrient loads to the Gulf of Mexico to reduce the size of the hypoxic area. These include recognition of the important differences in the agricultural sources of nitrogen and phosphorus, the role of atmospheric nitrogen, attention to phosphorus sources downstream from reservoirs, and better control of both nitrogen and phosphorus in close proximity to large rivers (Alexander et al., 2008).

Reductions in nutrient loads are imperative now, if not sooner. The Gulf of Mexico coastal ecosystem has reached a tipping point where less nitrate-N is required now to produce the same size “Dead Zone” as a smaller nitrogen load 20 years ago (Turner et al., 2008). There is also a stored carbon “history” in the offshore sediments that will continue to fuel organic matter decomposition and hypoxia for years to come. Experience from other systems and a coupled biological-physical model for the Louisiana shelf (Justić et al., 1997) indicate that it may take several years or longer to detect a response of the marine system to changes in the nutrient load. Also, it is possible that a new steady-state exists within the basin, balancing stored soil nitrogen, inputs, and flushing in response to precipitation and climatic variability. Thus, management actions within the basin may not result in reduced nitrogen flux to the Gulf of Mexico for many years. Recognizing these significant potential time delays is important in adaptive management strategies. In addition, changes in land use, particularly with the growing demand for corn-based ethanol, and the vagaries of climate may cause setbacks that are as yet unanticipated (Figure 16).

The 2008 Mississippi River discharge broke the record (since 1930) for the maximum flow in spring. With the increased acreage in corn, increased fertilization, higher than average concentrations of nitrate-N in the spring, and the record flow, a very high load of nitrate is predicted for May 2008 and, consequently, the largest predicted hypoxic zone to date. The cruise to map the “Dead Zone” will take place from July 21 to 29, 2008. It is imperative within the long-term strategy for nutrient management that public education communicates to stakeholders the management successes, system recoveries, and any seeming lack of accomplishments.

Nutrient Reductions Do Work

Reducing excess nutrient loading to estuarine and marine waters requires individual, societal, and political will. Proposed solutions are often controversial and may extract societal and economic

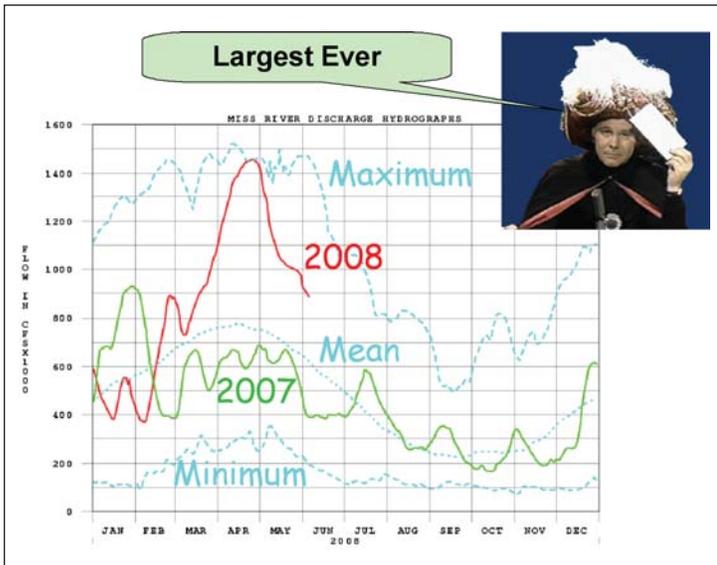


Figure 16. The daily Mississippi River discharge at Tarbert Landing, in cubic feet per second through early June of 2008 compared to 2007 (<http://www.mvn.usace.army.mil/eng/edhd/tar.gif>).

costs. 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 National Estuary Program for many U.S. estuaries, a Long Island Sound agreement for New York and Connecticut, the Hypoxia Action Plan for the Mississippi River basin, and international cooperation among the nations fringing the Baltic Sea as part of the Helsinki Commission.

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. But, success it is for examples such as the coral reefs in Kaneohe Bay and the improved water clarity and recovery of seagrass beds in Tampa and Sarasota Bays (Smith, 1981; Johansson and Lewis, 1992; Sarasota Bay National Estuary Program, 1995). While not considered a social and economic success, the reduction of nutrients into the northwestern Black Sea demonstrated the capacity of a large coastal ecosystem to recover from decades of excess nutrients.

The northwestern shelf of the Black Sea is an analog situation to

the Louisiana shelf because it too is an exposed shelf rather than an enclosed embayment and it is fed by large rivers. Bottom-water hypoxia on the northwestern shelf of the Black Sea was first documented in 1973 (Zaitsev, 1992) (Figure 17).

There is substantial evidence that eutrophication in the Black Sea is the result of large increases in the discharge of nitrogen and phosphorus to the Black Sea from the 1960s and 1970s (Mee, 2001). The typical scenario followed with increased nutrients triggering dense phytoplankton blooms, a decrease in seawater transparency, and an increase in the load of organic detritus reaching the seafloor (Tolmazin, 1985; Mee, 1992, 2001; Zaitsev, 1992). The high organic loading was followed by an expansion of oxygen-deficient waters over the northwestern shelf in depths of 8 to 40 m and over areas of the seafloor covering up to 40,000 km².

As a result of the dissolution of the former Soviet Union and declines in subsidies for fertilizers, the decade of the 1990s witnessed a substantially decreased input of nutrients to the Black Sea (Mee, 2001; Lancelot et al., 2002). For the first time in several decades, oxygen deficiency was absent from the northwestern shelf of the Black Sea in 1996 and receded to an area less than 1,000 km² in 1999 (Mee, 2001).

Just when Black Sea researchers were convinced that the northwestern shelf was moving towards recovery, late rainfall and higher temperatures triggered a new large-scale hypoxic event in 2001, endangering the slow recovery of the coastal ecosystem (Mee et al., 2005). Some think that the inclusion of many central and eastern European countries in the European Union will trigger economic and industrial growth and modernized agriculture that could again threaten Black Sea coastal water quality, but membership in the European Union will also bring common policies and regulations that will protect aquatic resources. The growing decline of coastal water quality and expansion of symptoms of eutrophication, as well as the proven successes of reducing nutrients, are reasons enough for us to continue and expand efforts to reduce nutrient over-enrichment.

Outlook

The continued and accelerated export of nitrogen and phosphorus to the world's coastal ocean is the trajectory to be expected unless societal intervention in the form of controls or changes in culture are pursued. Seitzinger et al. (2002) modeled future projections of dissolved inorganic nitrate (DIN) export from world rivers in a Business-as-Usual scenario and predicted that DIN

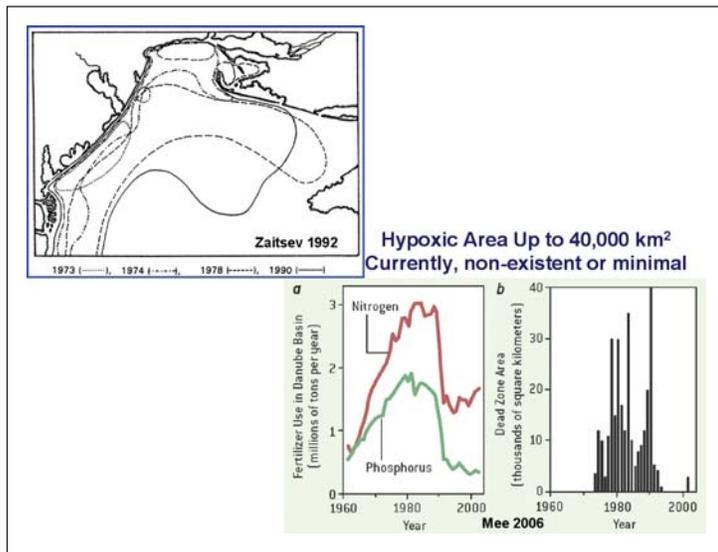


Figure 17. Upper left: the increasing size of the hypoxic area on the northwestern shelf of the Black Sea adjacent to the effluent of the Danube River (Zaitsev, 1992). Lower right: (a) the increase in nitrogen and phosphorus fertilizer use in the Danube river watershed, and (b) the increase, then decrease in the size of bottom-water hypoxia that paralleled the changes in nutrient loads (Mee, 2006). The nitrogen and phosphorus nutrient loads paralleled the respective fertilizer uses.

export rates increased from approximately 21 Teragrams of nitrogen per year (Tg N y^{-1}) in 1990 to 47 Tg N y^{-1} by 2050. Increased DIN inputs to coastal systems in most world regions were predicted by 2050. The largest increases were predicted for southern and eastern Asia, associated with predicted large increases in population, increased fertilizer use to grow food to meet the dietary demands of that population, and increased industrialization. Indeed, an incipient and large area of hypoxia is becoming persistent off the Changjiang River (Yangtze) in the East China Sea (Li and Daler, 2004). Others will follow.

With or without nutrient management scenarios, the projected increasing nutrient export trajectory will occur within a likely scenario of global climate change. The implications for coastal eutrophication and subsequent ecosystem changes, such as worsening conditions of oxygen depletion, are significant. A modeling study that examined the impacts of global warming on the annual discharge of the 33 largest rivers of the world (Miller and Russell, 1992) suggested that the average annual discharge of the Mississippi River would increase 20 percent if the concentration of atmospheric carbon dioxide (CO_2) doubled. If so, hypoxia would

intensify and expand on the Louisiana continental shelf (Justić et al., 1996, 1997, 2003a,b).

Future scenarios for eutrophication and hypoxia under an increasingly burgeoning population with excessive consumptive needs for food and fuel are disquieting when one conjures the trajectory of nutrient inputs and coastal ecosystem responses that occurred during the last half of the twentieth century and considers projections well into the twenty-first century. Still, we understand much more about the process, the causes, and the responses of the system to excess nutrients presently than in 1985 when Rosenberg (1985) predicted that eutrophication was to become the future coastal nuisance. Eutrophication has surpassed a categorization of “nuisance,” and nutrient over-enrichment has been labeled “the greatest pollution threat faced by the coastal marine environment” (National Research Council, 2000).

At the same time, scientists, resource managers, and the public are becoming increasingly aware of the environmental, social, and political issues surrounding eutrophication and have developed multi-faceted, multi-level, integrated and sound management plans to reduce nutrient loads to coastal waters and alleviate the symptoms of eutrophication. If we can collectively reduce nutrients to the level of success that pesticides such as Dichloro-Diphenyl-Trichloroethane (DDT) or sources of atmospheric deposition that led to acid rain were reduced, then there remains the potential to reverse current coastal water quality degradation while sustaining renewable resources and the economic livelihood of members of society.

Acknowledgements

While I, as an individual scientist, am singled out for the prestigious NWRI Athalie Richardson Irvine Clarke Prize, my accomplishments have not been singled-handed. Since my first trip offshore to the “Dead Zone” in a (too) small boat, our collaborative group has been steadily increasing the science and knowledge linking watershed use with coastal water quality. The voyage has been productive from the sense of scientific accomplishments and fulfilling with regard to the growing awareness of the public and policy makers to the Mississippi River-Gulf of Mexico linkages and similar areas nationally and globally.

The research that led to the scientific knowledge on patterns of eutrophication and oxygen depletion in the northern Gulf of Mexico was funded by the following agencies, grants, and initiatives:

- ▶ NOAA Nutrient Enhanced Coastal Ocean Productivity (NECOP) program.
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- ▶ Minerals Management Service (MMS) University Research Initiative and Coastal Marine Initiative.
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Finally, I would like to thank Mrs. Joan Irvine Smith, the Irvine Family, and the National Water Research Institute for deeming me the recipient of the prestigious NWRI Athalie Richardson Irvine Clarke Prize.



The 2008 Clarke Prize Honoree

NANCY N. RABALAIS, PH.D.



For over 25 years, Dr. Nancy N. Rabalais has dedicated her career to understanding and mitigating the effects of human-induced changes in water quality. She is renowned for her seminal research on understanding and characterizing hypoxia, or severe oxygen depletion, in water resources, bringing this crucial issue to the forefront of water science.

Hypoxia is an extensive and persistent phenomenon that is caused by increased nutrients in water. Nutrients can lead to excessive growth of algae, which in turn can damage marine habitats and harm marine organisms due to lack of oxygen in the water. These “dead zones” significantly impact commercial and recreational fisheries and the health of coastal environments.

Since the mid-1980s, Dr. Rabalais has been the driving force behind identifying and characterizing the dynamics of the large hypoxic region in the Gulf of Mexico, which receives excess nutrients from the Mississippi River. For instance, her team recognized that much of the nutrients in the Mississippi River

originated from agricultural runoff caused by increased fertilizer application and artificial soil drainage. Such efforts have resulted in national and international interest, such as an Action Plan endorsed by states, federal agencies, and tribes to reduce hypoxia through improved nutrient management in the Mississippi River watershed and coastal waters of the Gulf of Mexico.

From providing congressional testimony to working with local elementary schools, Dr. Rabalais consistently keeps the hypoxia issue before the scientific community, policy makers, and general public. She continues to conduct critical fundamental work in the area, and is considered one of the most prolific researchers focused on marine water quality. Currently, she serves as Executive Director and Professor of the Louisiana Universities Marine Consortium in Chauvin, Louisiana.

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