Nutrients and Hypoxia in the Gulf of Mexico — An Update on Progress, 2008

By C.S. Snyder

Based on data presented here and in the U.S. Environmental Protection Agency's Science Advisory Board (EPA SAB) 2008 report, there is reason to believe that declines in discharge of N and P to the Gulf of Mexico are proceeding through voluntary actions by farmers, their advisers, and their suppliers. Driven by global economic pressures, local and personal profitability goals and objectives, and a greater environmental consciousness and stewardship ethic, farmers and practitioners are increasingly implementing fertilizer BMPs. These accomplishments are noteworthy and herald progress toward improved fertilizer nutrient use efficiency, which may lead to reductions in N and P loss from farm fields and agricultural watersheds.

Since 1985, the areal extent of hypoxia (≤2 mg/L of dissolved oxygen) in the shallow coastal waters (< 30 m or 100 ft.) of the northern Gulf of Mexico has been estimated annually in late July by scientists with the Louisiana Universities Marine Consortium (LUMCON). **Figure 1** shows the extent of hypoxia beginning in 1985 and through 2007. Historic evidence suggests hypoxia is a natural event, but current science indicates hypoxia in the Gulf has occurred more frequently and extensively in the last half century. These contemporary changes in the size and duration of the hypoxic zone are thought to be most related to nutrient discharges, specifically N and P discharges from the Mississippi and Atchafalaya River Basin (MARB).

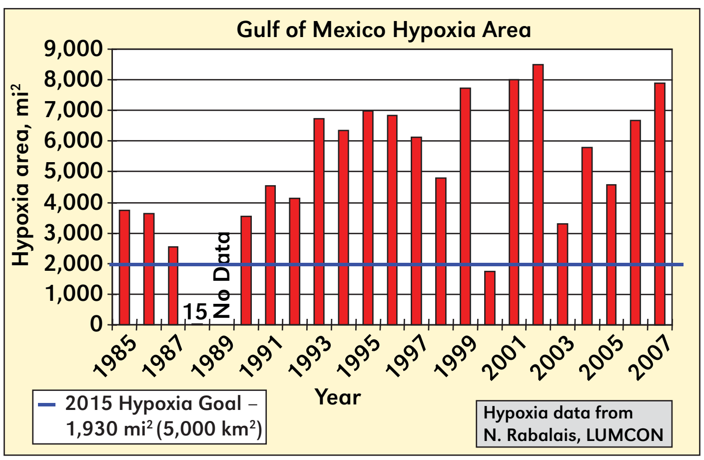
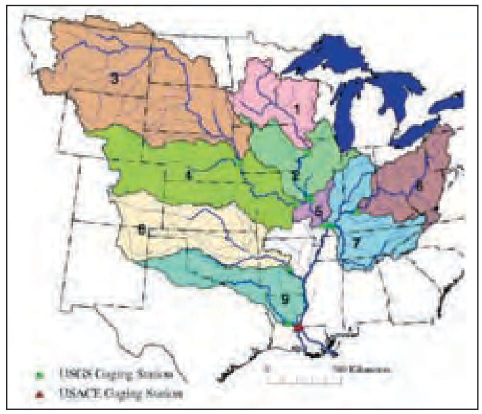


Figure 1. Areal extent of hypoxia in the northern Gulf of Mexico, as determined by annual cruises conducted in late July. Data source: N. Rabalais, LUMCON.

Federal, state, and tribal authorities developed an Action Plan and defined within-Basin goals and the goal of reducing the hypoxic zone in the Gulf of Mexico to a 5-year running average of 5,000 km² (1,930 mi²) by 2015 (MR/GMWNTF, 2001). Since 2001, knowledge has expanded on the complexity of factors (e.g. climate, weather, basin morphology, coastal water circulation patterns, water retention times, freshwater inflows, stratification of freshwater over saltwater, mixing, nutrient loadings, and loss of processing marsh lands along the Louisiana coast) that contribute to the development of hypoxia in the Gulf. For example, a recent report by Hetland and DiMarco (2008) has exposed some of the complexities associated with coastal physical processes, and factors that interact with the biology of the ecosystem, which affect hypoxia development and persistence east and west of the shelf region south of Terrebone Bay in Louisiana. These two authors suggest that a water stratification envelope may be the dominant factor affecting the areal extent of hypoxia along the Louisiana-Texas shelf, as opposed to nutrients delivered by the Mississippi and Atchafalaya discharges.



Location of nine large sub-basins comprising the MARB that are used for estimating nutrient fluxes (from Aulenbach et al., 2007).

At the request of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (MR/GMWNTF), EPA impaneled a team of leading scientists to form a hypoxia Science Advisory Board to reassess nutrient load reductions achieved, the responses of the hypoxic zone and associated water quality and habitat conditions, and economic and social effects since the 2001 Action Plan (MR/GMWNTF, 2001) was released. The SAB reported: *"Hypoxia can occur naturally in deep basins, fjords, and oxygen minimal coastal zones associated with upwelling. However, nutrient-induced hypoxia in shallow coastal and estuarine systems is increasing worldwide"* (EPA SAB, 2008). The SAB report also stated that *"recent science has affirmed the basic conclusion that contemporary changes in the hypoxic area in the northern Gulf of Mexico are primarily related to nutrient fluxes from the MARB."* A new Action Plan is in development and a draft has been released to the public (MR/GMWNTF, 2008).

Former N discharge reduction goals (MR/GMWNTF, 2001) were aimed principally at NO_3-N discharge reduction (actually, reported as the combined measure of NO_3^- and NO_2^- forms of N), but the 2008 EPA SAB report recommended reductions in

Abbreviations and notes for this article: N = nitrogen; P = phosphorus; BMPs = best management practices; NO_3^- = nitrate; NO_2^- = nitrite; NH_4^+ = ammonium; UAN = urea ammonium nitrate; NO_y = reactive N oxides plus the compounds produced from their oxidation.

total N discharge: the combination of organic and inorganic N (NH_4^+ and NO_3^-). In addition, significant reductions in total P discharge were also recommended. In contrast to prior thinking and conventional wisdom, research has shown that P discharge plays a role in the initiation of phytoplankton (i.e. algae) blooms in the shallow, lower salinity waters nearer the Gulf shore.

To reduce the size of the hypoxic zone and improve water quality in the MARB, the EPA SAB (2008) panel recommended a dual nutrient strategy:

- reduce total N discharge at least 45% (to approximately 870,000 metric tons/yr or 960,000 tons/yr), and
- reduce total P discharge at least 45% (to approximately 75,000 metric tons/yr or 83,000 tons/yr).

Results of some predictive modeling studies have led some authors to suggest that increased precipitation amounts and intensities associated with climate change may create conditions that would require even larger nutrient discharge reductions (e.g. 50 to 60%) to shrink the size of the hypoxic zone (Donner and Scavia, 2007; Justic et al., 2007).

The Atchafalaya River discharge, because of the Mississippi River diversion (mandated by legislation since the mid-1970s at 30% of the combined flow of the Mississippi River and the Atchafalaya River) is contributing about 50% of the freshwater to the Louisiana-Texas shelf, while the remaining 50% of the freshwater is discharged via the main Mississippi River plume southeast of New Orleans. These massive inputs of freshwater, coupled with weak tidal energies, seasonally variable stratification strength, high water temperature, and wind effects from fronts and storms result in complex coastal circulation and stratification physics, which exert an important influence on the seasonal development and persistence of hypoxia.

Trends in Water, N, and P Discharge

The following trends in N and P discharge were identified in the EPA SAB (2008) report:

- Comparisons of 2001 to 2005 (most recent 5-year data) with the reference period of 1980 to 1996 showed the following. Also see **Table 1**.
  - annual average water flow (flux) to the Gulf decreased about 6%, while spring flow (April-June) decreased 11%,
  - annual NO_3-N discharge decreased 15%, while spring NO_3-N discharge decreased 12%,
  - annual total Kjeldahl N (organic + NH_4-N) discharge decreased 30%, while spring discharge decreased 32%,
  - annual total N discharge decreased 21%, while spring total N discharge decreased 19%, and
  - annual total P discharge increased 12%, while spring total P discharge increased 10%.
- Clearly, these annual and spring N and P discharge changes are not directly proportional to changes in the freshwater volume delivered to the Gulf. Nutrient management, cropping patterns, and areas within the MARB where leaching, runoff, and drainage occur, and coastal ocean physics are also important factors that must be considered in plans to reduce nutrient loss to the Gulf.
- It is important to note that the 21% decline in total N discharge from the MARB to the Gulf of Mexico in 2001 to 2005 is an achievement of two-thirds of the 30% reduction objective recommended in the 2001 Action Plan to help meet the 5-year running average 5,000 km^2 (1,930 mi^2) hypoxic area goal. However, this sizeable reduction in total N discharge does not appear to have affected the annual size of the hypoxic zone (see **Figure 1**). The size of the zone in 2007 was the third largest recorded since 1985.
- Contributions of the major MARB sub-basins to water flow, and to total N and total P discharge delivery to the Gulf of Mexico, are shown in **Table 2.** These same nutrient contributions are shown in **Table 3** on a land area basis. The Upper Mississippi Sub-basin and the Ohio-Tennessee Sub-basin combined account for the majority of the freshwater flow and N and P delivery to the Gulf, while the other sub-basins also contribute significantly. On a per hectare land area basis, the Lower Mississippi Sub-basin contributes total P in a magnitude similar to the Upper Mississippi and the Ohio-Tennessee Sub-basins (**Table 3**).
- Total freshwater discharge to the Gulf varies considerably among years **(Figure 2)**, has increased since 1955, since the 1970s, and…as noted above…since the 1980 to 1996 period (**Table 1**).
- Since the mid-1980s, annual NO_3-N, NH_4-N, particulate/organic-N, and total N discharge (flux) from the MARB **(Figure 3)** have declined, especially the total N delivered to the Gulf.
- Total P discharge has remained constant or increased slightly since the 1980s, while orthophosphate P and silicate discharges have declined slightly **(Figure 4).**
- Spring (April-June) discharge (flux) of freshwater, NO_3-N, Kjeldahl N, and total N from the MARB have all declined since the early 1980s (**Figure 5**).
- Spring (April-June) discharge (flux) of soluble reactive P (orthophosphate), total P and silicate from the MARB have also declined since the early 1980s (**Figure 6**).

Table 1. Average annual and spring (April-June) combined water flow, NO_3-N, total Kjeldahl N (organic N + NH_4-N), and total N discharge from the combined Mississippi and Atchafalaya Rivers to the Gulf of Mexico for 2001 to 2005 compared against the reference period 1980-1996. Source: EPA SAB, 2008.

	1980-1996	2001-2005	Change
	million m^3 (water) or million metric tons		%
Annual			
Water	692,500	652,500	-6
NO_3-N	0.96	0.81	-15
Total Kjeldahl N	0.61	0.43	-30
Total N	1.58	1.24	-21
Spring			
Water	236,800	210,600	-11
NO_3-N	0.38	0.33	-12
Total Kjeldahl N	0.21	0.14	-32
Total N	0.59	0.48	-19

Table 2. Average nutrient discharge for the five large sub-basins in the Mississippi–Atchafalaya River Basin for the 2001-2005 water years (EPA SAB, 2008). Values in parentheses indicate % of total Basin discharge.

Sub-basin	Land Area		Water flow	NO_3-N	NH_4-N and organic N (Total Kjeldahl N)	Total P
	km^2	mi^2	million m^3/yr	- - - - - - - -	1,000 metric tons/yr	- - - - - - - -
Upper Mississippi[1]	493,900	190,600	116,200 (18)	349 (43)	136 (32)	40 (26)
Ohio-Tennessee	525,800	203,000	279,800 (43)	335 (41)	175 (41)	59 (38)
Missouri	1,353,300	522,400	60,080 (9)	79 (10)	84 (20)	30 (20)
Arkansas-Red	584,100	225,500	67,200 (10)	29 (4)	44 (10)	9 (6)
Lower Mississippi[1]	183,200	70,700	129,550 (20)	22 (3)	-8 (-2)	16 (10)

[1] Nutrient discharge calculated by differences. Negative values occur downstream where a downstream site had a lower discharge than the upstream site, that result in errors in discharge estimates or a real net loss of nutrients.

The MARB is one of the largest river systems in the world.

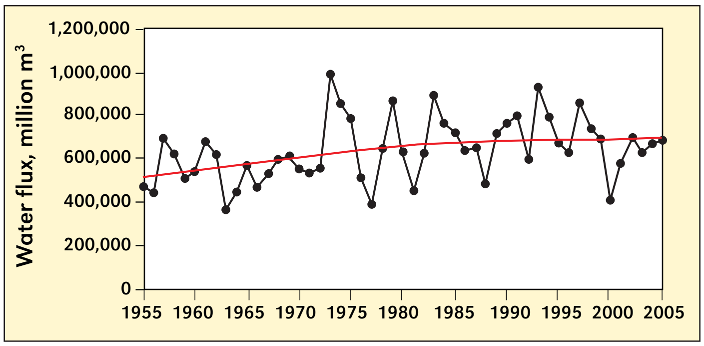


Figure 2. Annual water discharge (flux) for the combined Mississippi and Actchafalaya Rivers to the Gulf of Mexico, 1955-2005 (from EPA SAB, 2008). Red curve represents statistically-based, smoothed trend.
Source: EPA SAB, 2008.

Table 3. Average annual nutrient yields for the five large sub-basins in the Mississippi-Atchafalaya River Basin for water years 2001-2005. Source: EPA SAB, 2008.

Sub-basin	NO_3-N	NH_4-N and organic N (Total Kjeldahl N)	Total P
	- - - - - - - -	kg/ha/yr	- - - - - - - -
Upper Mississippi	7.1	2.7	0.8
Ohio-Tennessee	6.4	3.3	1.1
Missouri	0.6	0.6	0.2
Arkansas-Red	0.5	0.8	0.1
Lower Mississippi	1.2	-0.5	0.9

- From 2001 to 2005, based on data from the U.S. Geological Survey (USGS), the upper Mississippi and Ohio-Tennessee River sub-basins contributed about 82% of NO_3-N, 69% of the total Kjeldahl N (organic N plus NH_4-N), and 58% of total P discharged annually to the Gulf of Mexico, while these sub-basins represent only about 31% of the entire MARB drainage area.
- From 2001 to 2005, point sources (in contrast with diffuse nonpoint sources) represented 22% of the annual average total N and 34% of the annual average total P discharged to the Gulf.

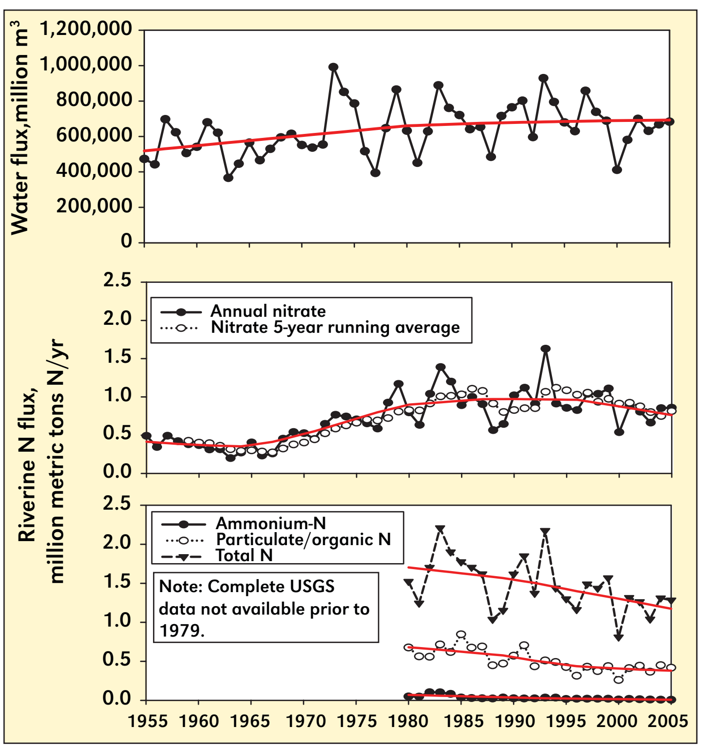


Figure 3. Annual N discharge (flux) for the Mississippi-Atchafalaya River Basin for 1955-2005. Red curves represent statistically-based, smoothed trends.
Source: EPA SAB, 2008.

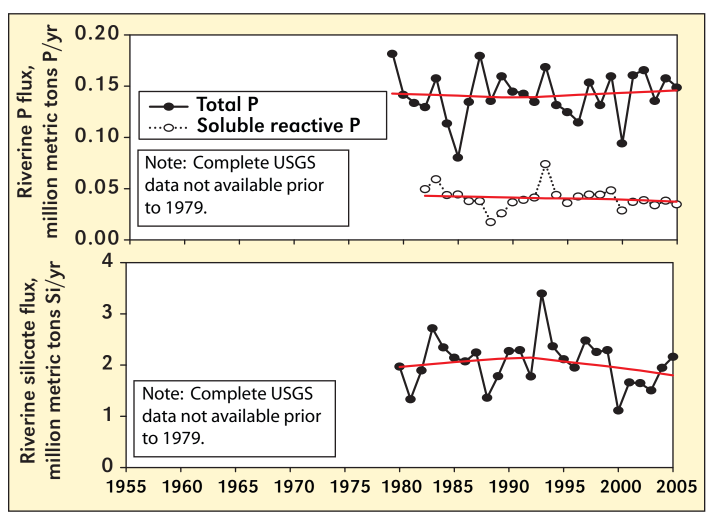


Figure 4. Annual P and silicate discharge (flux) for the Mississippi-Atchafalaya River Basin for 1979-2005. Red curves represent statistically-based, smoothed trends.
Source: EPA SAB, 2008).

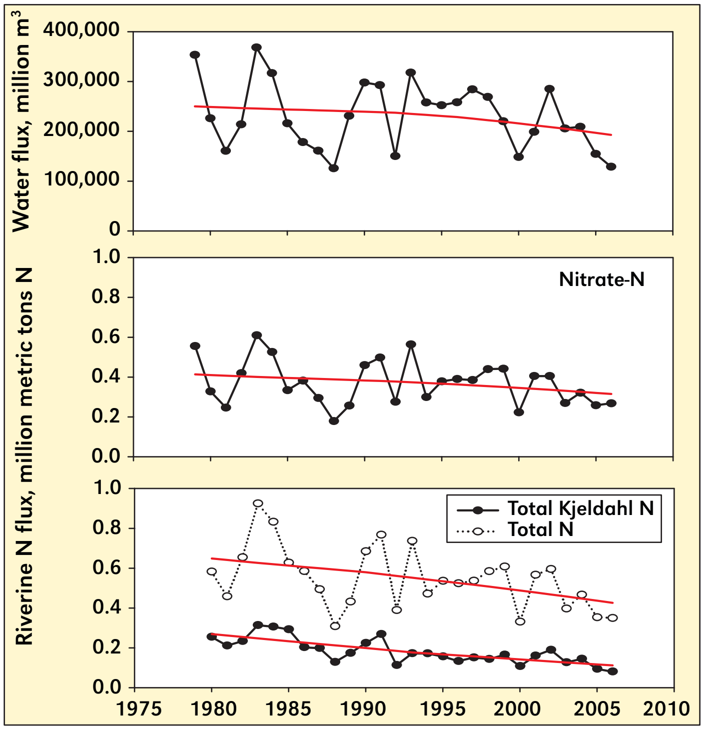


Figure 5. Spring (April-June) water flow, NO_3-N, Kjeldahl N, and total N discharge (flux) for the Mississippi-Atchafalaya River Basin for 1979-2006. Red curves represent statistically-based, smoothed trends. Source: EPA SAB, 2008.

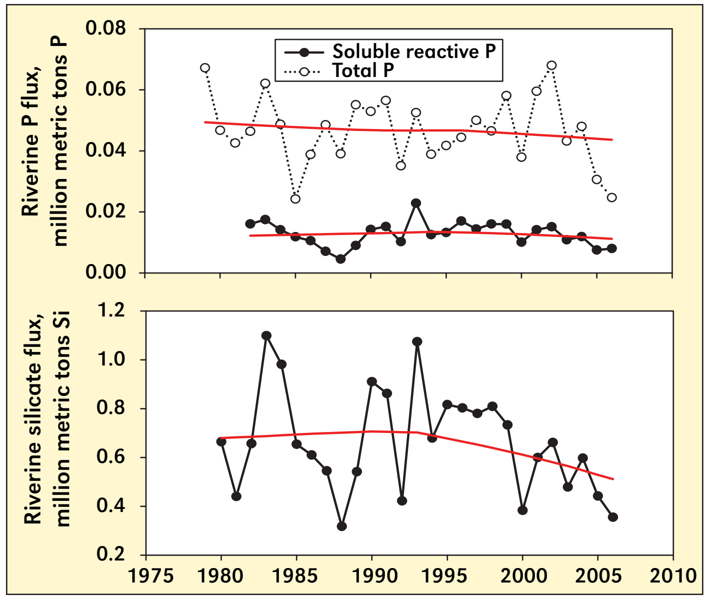


Figure 6. Spring (April-June) P and silicate discharge (flux) for the Mississippi-Atchafalaya River Basin for 1979-2006. Red curves represent statistically-based, smoothed trends. Source: EPA SAB, 2008.

Correlations between N and P Discharge and Hypoxia

- Correlations of the discharges of total N, NO_3-N, total P, and orthophosphate-P with the annual size of the hypoxic zone for 1985 through 2006 (**Table 4**) show the following.
  - o Relationships of annual hypoxia with annual total N discharge are weaker than relationships with annual total P discharge. The portion of the total variation in the annual size of Gulf hypoxia explained by annual total N discharge was less than 2% (R^2 =0.019), while annual total P discharge explained 4% (R^2 =0.04), of the variation in the annual size of hypoxia.
  - o Relationships of hypoxia with annual discharge of NO_3-N and annual discharge of orthophosphate-P are slightly stronger compared to annual total N and total P discharges. However, the correlations are still weak ($R^2 < 0.25$).

Table 4. Portion of the variability in the size of the annual hypoxic area in the northern Gulf of Mexico explained by the discharge of N and P annually and in the spring (April-June), 1985-2006.

Nutrient	Annual Discharge	Spring Discharge
	---------- R^2* ----------	
Total N	0.019	0.148
Total P	0.040	0.187
Nitrate-N	0.128	0.293
Orthophosphate-P	0.205	0.395

*Based on simple linear regression.

  - o Relationships of hypoxia with spring discharges of total N, total P, NO_3-N, and orthophosphate-P are stronger compared to annual discharges.
    - ▪ Spring discharges of these nutrients explain more of the annual variation in the size of the hypoxic zone than do the annual total discharges of these nutrients.
    - ▪ The soluble forms of N (NO_3^-) and P (orthophosphate) discharged in the spring show a relationship with annual hypoxia at least twice as strong as relationships with the total quantities of N and P discharged in spring.
    - ▪ These spring-discharge relationships clearly point to opportunities for skilled nutrient management and implementation of improved fertilizer BMPs to help retain more N and P within farm fields, and to improve crop N and P use efficiencies (Snyder and Bruulsema (2007).
    - ▪ These N and P spring-discharge relationships with annual hypoxic area also lend support to arguments that other factors besides N and P discharge (e.g. stratification, specific circulation patterns, "ecosystem memory", etc.) may have equal or more dominant effects on hypoxia development and persistence. For example, Turner et al. (2006) reported on the influence of seasonal nutrient discharge and hypoxia in the northern Gulf of Mexico for 1985 through 2004. They indicated that because of "ecosystem memory" or residual effects, some passage of time may be required before effects on dissolved oxygen concentrations are experienced…even after significant reductions in nutrient discharge to coastal waters have occurred.

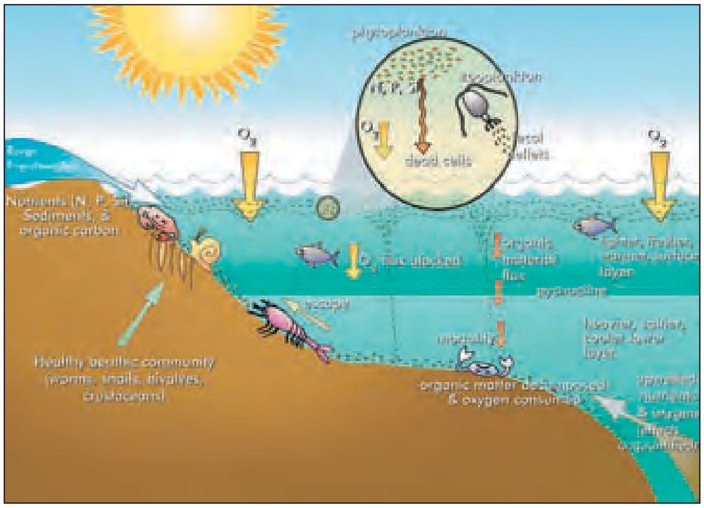


Illustration from EPA

This schematic describes some of the processes contributing to hypoxia development.

Trends in Nutrient Mass Balances

- Recoverable manure (from confined animal feeding operations) represents less than about 6% of the total N (fertilizer, legume, recoverable manure) inputs in North America (Fixen and Johnston, 2002) and within the MARB. From 1990 to 1996, the USDA-estimated crop acreage receiving manure was as follows: corn, 17%; soybean, 6%; winter wheat, 3%; and cotton, 4% (Ludwick and Johnston, 2002). Although recoverable manure may be an important N and P source locally, it should probably not be considered a major nutrient input source within the entire MARB.
- Nutrient mass balances were estimated for the MARB in the EPA SAB (2008) report:
  - o Analyses of the available data indicated that net anthropogenic N inputs have declined in the past decade (**Figure 7**) because of increased crop yields (resulting in increased N removal in crop harvest), reduced or redistributed livestock populations, and small changes in N fertilizer N inputs.
    - About 22% of the total N and 34% of the total P discharged to the Gulf yearly are attributed to point sources. The remainder of total N and total P inputs in the MARB are estimated to come from non-point sources. The report stated: "Components of the N mass balance such as denitrification, biological N_2 fixation, manure N, and soil N pool processes such as mineralization and immobilization are not measured each year. Only biological N_2 fixation and manure N can even be estimated, with the other fluxes having little data available to make calculations. Point sources export N and P directly to rivers, yet their contributions continue to be estimated from permits." So, the values shown in **Figures 7 and 8** should be viewed guardedly, with some understanding about these estimate uncertainties.
    - From 1999-2005, net anthropogenic N input estimates and calculations indicated that 54% of non-point source net N inputs in the MARB

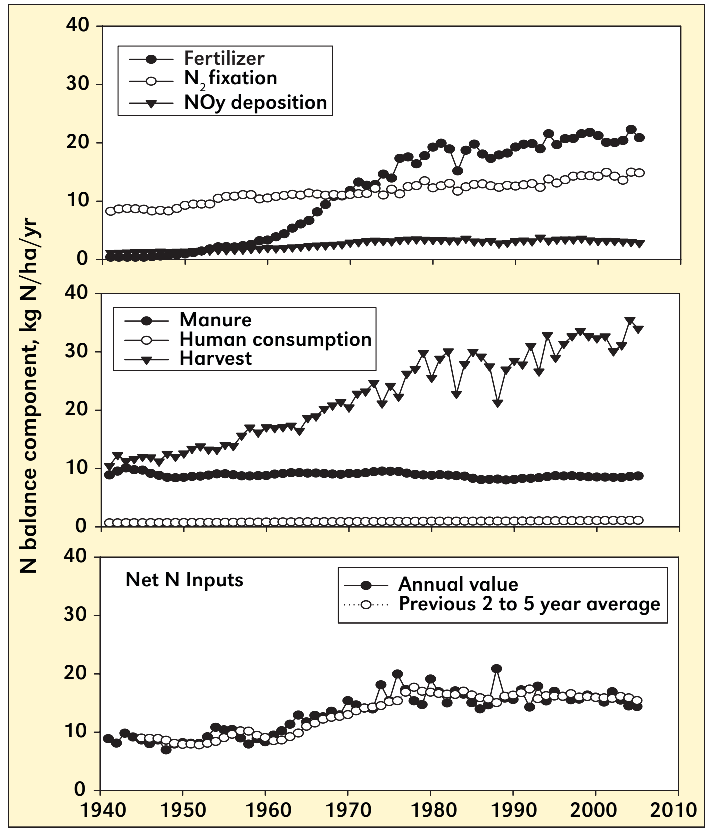


Figure 7. Nitrogen mass balance and net inputs for the Mississippi-Atchafalaya River Basin through 2005.
Source: EPA SAB, 2008.

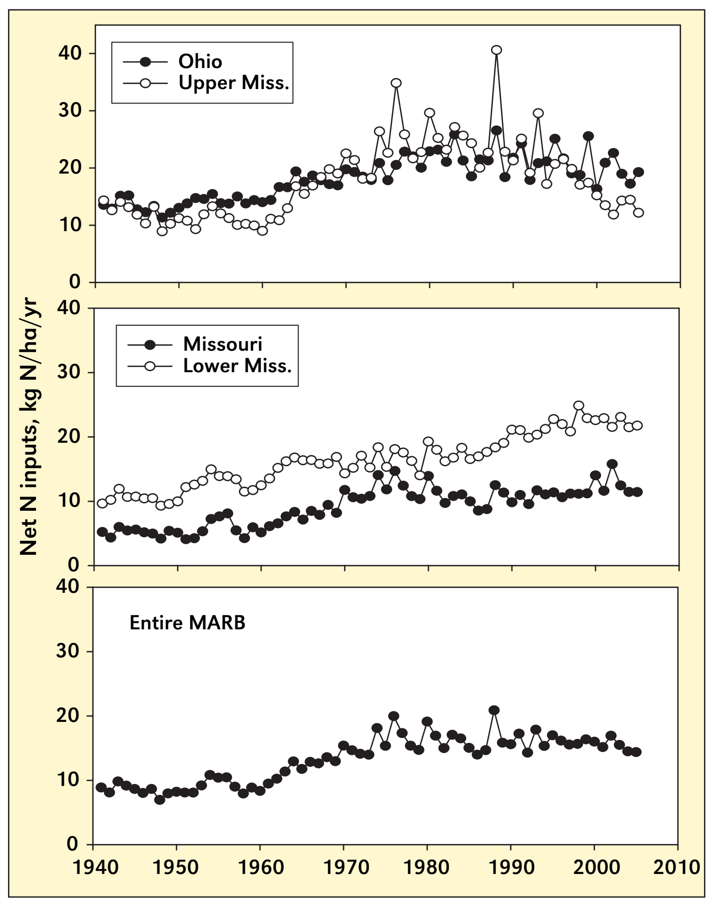


Figure 8. Nitrogen mass balance and net inputs for major regions of the Mississippi-Atchafalaya River Basin through 2005.
Source: EPA SAB, 2008.

were from fertilizer, 37% from biological N fixation, and 9% from atmospheric deposition.

- "Increased crop yield trends, improved plant genetic selection, and pest control may also be contributing to the reduced NO_3-N transported to the northern Gulf of Mexico (NGOM) since the mid-1990s, and the steady decline in total N delivered to the NGOM since the 1980s. Any reductions in N application rates could threaten attainment of high crop yields, which are vital to profitable production, and which have contributed in some measure to the reductions in net N inputs and riverine N discharge" (EPA SAB, 2008).
- Mass balances of N in the upper Mississippi River sub-basin (**Figure 8**) indicate that under the tile-drained corn and soybean management system currently in place, depletion of soil organic N pools may be occurring.
- Net anthropic P inputs for the MARB have decreased in the past decade (**Figure 9**) in association with reduced P fertilizer applications and increased crop yields (resulting in increased P removal in crop harvests).
- Increased crop yields and harvest nutrient removal in the Upper Mississippi and the Ohio River sub-basins have caused the greatest impact on declines in estimated net anthropogenic N inputs and net anthropic P inputs for the entire MARB (**Figures 8 and 9**).

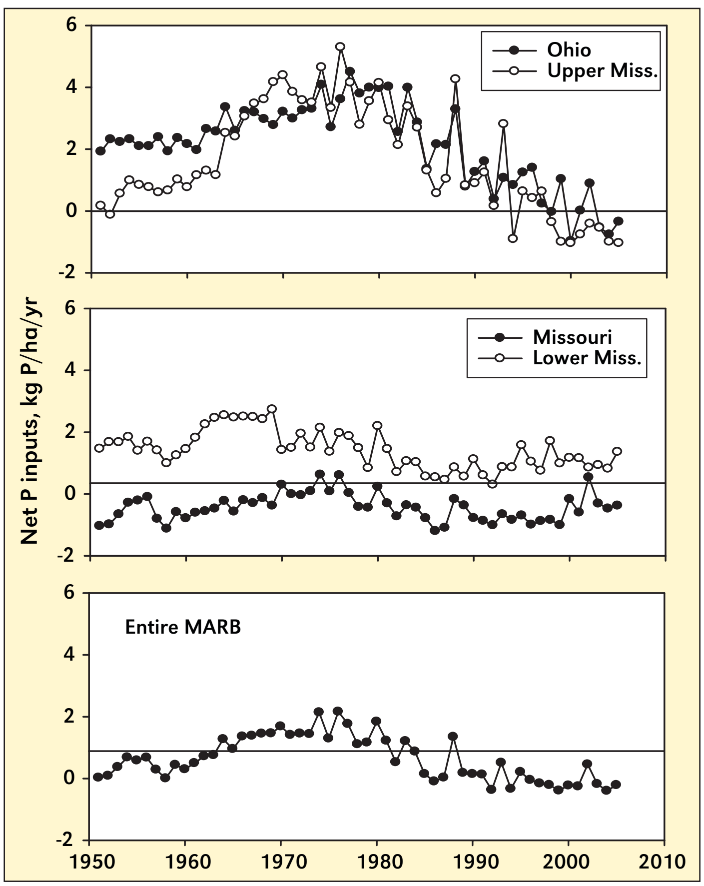


Figure 9. Phosphorus mass balance and net inputs for major regions of the Mississippi-Atchafalaya River Basin through 2005. Source: EPA SAB, 2008.

Fertilizer N Consumption and Shifts Among Sources

In the entire MARB, fertilizer N consumption has been relatively flat or increased slightly in the last two decades (**Figure 7**). In the Midwest, where the bulk of the fertilizer N and P are consumed, and where much of the USA corn crop is produced, there have been shifts in the N tonnages among anhydrous ammonia, UAN, and urea. For example, the combined N consumption of urea and UAN solution has increased and recently surpassed anhydrous ammonia N consumption in six leading corn-producing states (IA, IL, IN, MN, NE, and OH) (**Figure 10**). These shifts among N sources may indicate some change toward spring application timing away from fall applications of anhydrous ammonia, some preference in use of sources toward those presenting lower human health (e.g. direct contact) risks; or the changes may represent shifts in the supply infrastructure, which may translate into local changes in availability of some N sources to farmers.

Corn is the principal N consumer of the crops planted in the MARB. Corn yields have increased since 1990 from 126 bu/A (7.94 t/ha) to 160 bu/A (10.08 t/ha) in 2006 (**Figure 11**). As discussed above, higher crop yields have resulted in increased N removal in harvested grain, with only small increases in N fertilization (**Figures 7 and 10**). The net effect is lower net

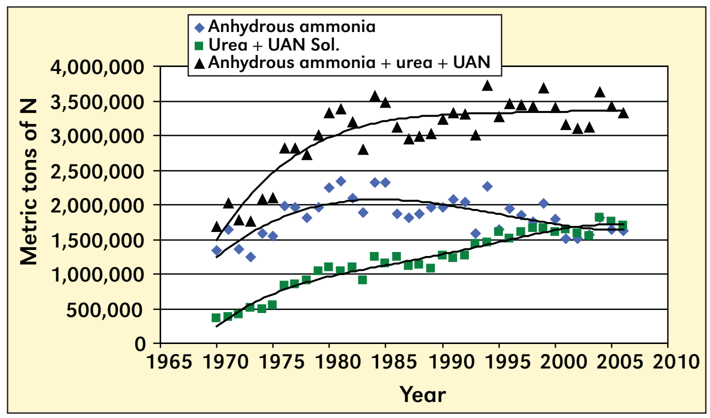


Figure 10. Changes in the consumption of principal fertilizer N sources used in the six leading corn producing states (IA, IL, IN, MN, NE, and OH) for years ending June 30. Sources: AAPFCO, personal communication with H. Vroomen of The Fertilizer Institute; EPA SAB, 2008.

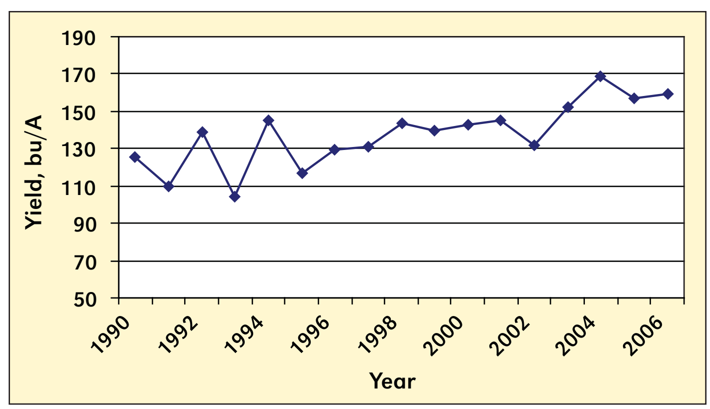


Figure 11. Average corn yields in six leading corn-producing states (IA, IL, IN, MN, NE, and OH), 1990-2006. Source: USDA National Agricultural Statistics Service.

N input to the lands within the MARB (**Figure 8**).

Conclusions

Based on data presented here and in the EPA SAB (2008) report, there is reason to believe that declines in discharge of N and P to the Gulf of Mexico are proceeding through voluntary actions by farmers, their advisers, and their suppliers. Driven by global economic pressures, local and personal profitability goals and objectives, a greater environmental consciousness and stewardship ethic, farmers and practitioners are increasingly implementing fertilizer BMPs. These accomplishments are noteworthy and herald progress toward improved fertilizer nutrient use efficiency, which may lead to further reductions in N and P loss from farm fields and agricultural watersheds.

Increased crop yields, improved plant genetic selection, and improved pest control may all be contributing to the lowered net anthropic N and net anthropic P inputs observed in the last decade or more. These environmental benefits are reflected in lower N and P delivery to the Gulf of Mexico during the peak spring (April-June) discharge. Any actions that could result in reductions in appropriate fertilizer N application rates could threaten attainment of high crop yields. Efficient attainment of high crop yields, which are vital to profitable production and essential to meet the food, fiber, and fuel demands of a growing world population, are contributing to reductions in net N inputs and net P inputs and reductions in delivery of N and P to the Gulf of Mexico.

Farmers will need to maintain their vigilance and improve their skills to achieve further gains in nutrient use efficiency. The fertilizer industry, crop advisers, agricultural consultants, natural resource professionals…public and private partners…are dedicated to reducing and minimizing the environmental footprints associated with commercial fertilizer use. Progress is being made, more is expected, and there is good reason for optimism as knowledge expands, behaviors change, and new technologies become available. We sincerely hope that through these efforts, water quality can be improved throughout the MARB and within the northern Gulf of Mexico. BC

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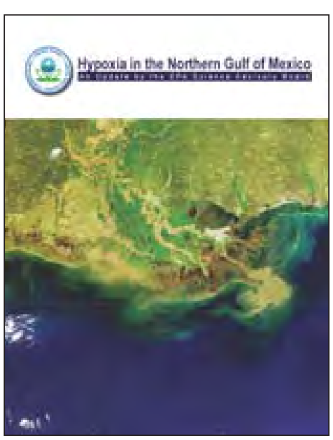

This image shows the cover of the 2008 Hypoxia SAB Report.

Increased crop yields, improved plant genetics, and improved pest control may be reflected in lower N and P discharge to streams and rivers.

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