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Progress in Reducing Nutrient Loss in the Mississippi River Basin – But Effects on Gulf Hypoxia Still Lag

By C.S. Snyder, International Plant Nutrition Institute

Nutrient losses *from farm fields remain major economic and environmental concerns in the Mississippi River Basin (MRB). Current loss rates of nitrogen (N) can represent a substantial profit loss to many growers. Losses of both N and phosphorus (P) can negatively affect water quality in the streams and rivers within the Basin, and in the northern Gulf of Mexico. This report identifies trends in N and P use from 1987 to 2012, MRB and sub-Basin partial N and P balances, hypoxia in the Gulf of Mexico, and highlights progress toward reductions in nutrient losses. These results: 1) underscore the need for expanded implementation of beneficial 4R nutrient management, and complementary soil and water conservation practices; 2) help emphasize the importance of conducting long-term, systems-level 4R nutrient management research; and 3) point to the need for N and P performance monitoring and tracking at field, farm, and watershed scales.*

What is the Mississippi River Basin?

The Mississippi River Basin or watershed (MRB), also referred to as the Mississippi-Atchafalaya River Basin (MARB), is the world's third largest watershed, which covers about 1.2 million (M) square miles (3.1 M square km) and drains 41% of the conterminous U.S. (**Figure 1**). The Mississippi River itself is about 2,350 miles in length (2nd longest in U.S. after the Missouri River), and is the main stem of a networked system of navigable waterways that cover about 12,350 miles, not including the 1,173 miles of the Gulf of Mexico Intracoastal Waterway. The Mississippi River-Missouri River combination globally ranks

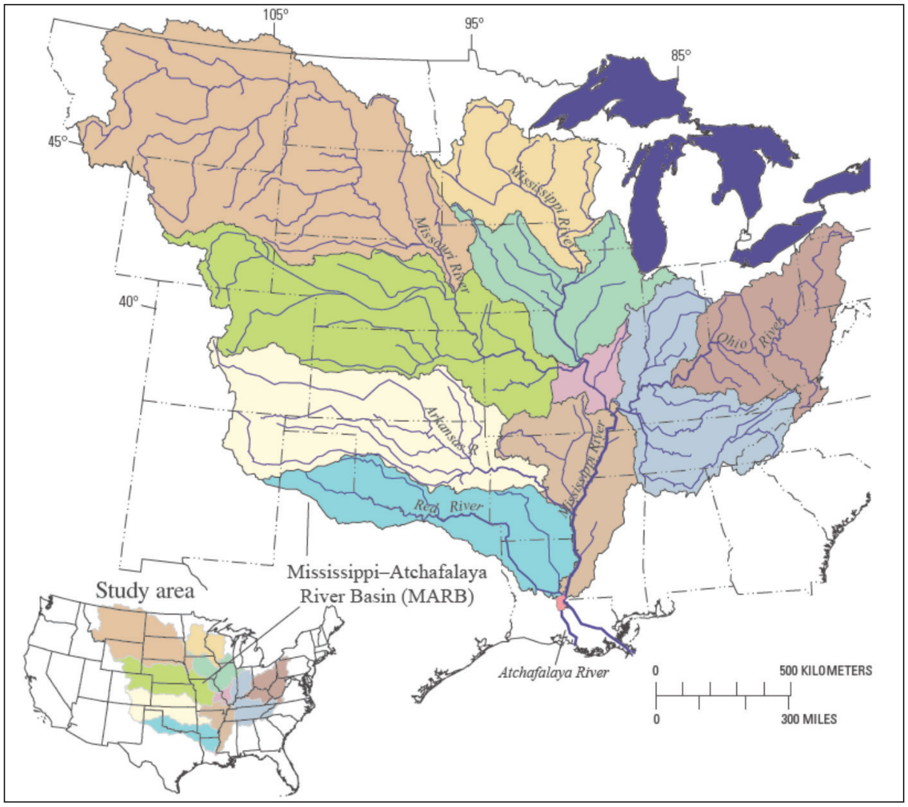

Figure 1. Mississippi River Basin (MRB) within the conterminous U.S. and part of Canada. Source: Battaglin et al., 2010.

International Plant Nutrition Institute (IPNI) 3500 Parkway Lane, Suite 550, Peachtree Corners, Georgia 30092-2844 USA
Phone: 770-447-0335; E-mail: info@ipni.net; Website: www.ipni.net For Issue Review Series visit http://www.ipni.net/IssueReview

fourth in length (3,710 mi or 5,970 km); following the Nile (4,160 mi or 6,693 km), the Amazon (4,000 mi or 6,436 km), and the Yangtze Rivers (3,964 mi or 6,378 km).

What is the MRB's importance to U.S. agriculture and society: crop production and fertilizer consumption?

The MRB includes parts or all of 31 states and parts of two Canadian Provinces, 33 major river systems, 207 estuaries, and is home to about 30% of the U.S. population. It encompasses >55% of the U.S. agricultural land (Goolsby and Battaglin, 2000) and >75% of the corn, cotton, rice, sorghum, wheat, and forage lands. In 2016, the total value of all crop production in the conterminous U.S. was about US$184 billion (B); with field crops accounting for $143.4 B, commercial vegetable crops $13.4 B, and fruit and nut crops (2015 data) $27.1 B (USDA NASS, 2016). The value of field and miscellaneous crop production (not including commercial vegetables, fruits, or nuts) within the MRB in 2016 was estimated at $131.6 B. **Farms in the MRB represent >90% of the conterminous U.S. field and miscellaneous crop production value in 2016.**

Based on the reported fertilizer consumption data through 2012, assembled by the Association of American Plant Food Control Officials (AAPFCO, 2017) and data from IPNI's Nutrient Use Geographic Information System (NuGIS; IPNI, 2012b), estimated agricultural fertilizer nitrogen (N) and phosphate (P_2O_5) consumption within the MRB, averaged 63 and 54% respectively, of the U.S. total agricultural fertilizer N and P_2O_5 consumption from 1987 to 2012 (**Figure 2**).

The commodities and goods produced in the MRB represent about 92% of the nation's agricultural exports; 78% of the world's exports in feed grains and soybeans, and most of the livestock and hogs produced nationally. Sixty percent of all grain exported from the U.S. is shipped on the Mississippi River through the Port of New Orleans and the Port of South Louisiana, according to the U.S. National Park Service.

More than 70 M people live within the MRB, and about 50 cities and 15 M people use the Mississippi River for their daily water supply. In addition, the MRB provides tremendous fish, waterfowl, and other wildlife habitat and ecosystem services; with more than 60% of all North American birds using the MRB as their migratory flyway. Clearly, the Mississippi River and MRB are highly valuable resources; vital to national and regional commerce, the economy of the U.S., and fish, waterfowl, and other wildlife habitat.

Combined with its largest distributary, the Atchafalaya River, the Mississippi River discharged an annual average of 676 km^3 of water into the Gulf of Mexico from 1985 through 2015 (https://toxics.usgs.gov/hypoxia/mississippi/flux_ests/delivery/index.html). That volume of annual discharge is equivalent to about 8 inches (20 cm) of water across the entire MRB (USGS, 2005). From Rock Island, Illinois to Head of Passes, Louisiana, there are 3,500 miles (about 5,630 km) of levees; which are earthen dams constructed parallel to a waterway, to contain water (Alexander et al., 2012). Such levees are crucial in preventing flood damage to cities and farms, but also prevent natural overflows and the delivery of sediment and nutrients onto adjacent floodplains; which significantly reduces opportunities for lowland and wetland ecosystems to retain and process the Mississippi River's (and tributaries') sediment and nutrient loads. Much of the sediment and nutrient loads that were once distributed along the MRB floodplain and within coastal estuaries and marshlands, are now channeled more directly, and farther out, into the Gulf of Mexico via the Mississippi River birdfoot delta (**Figure 3**). These factors may be contributing to some of the large erosional loss of saltwater wetlands and coastal marshes (>25 mi^2 or 66 km^2 per year). Those coastal marshes, have provided vital fisheries habitat and serve as natural nutrient utilization and filtration systems.

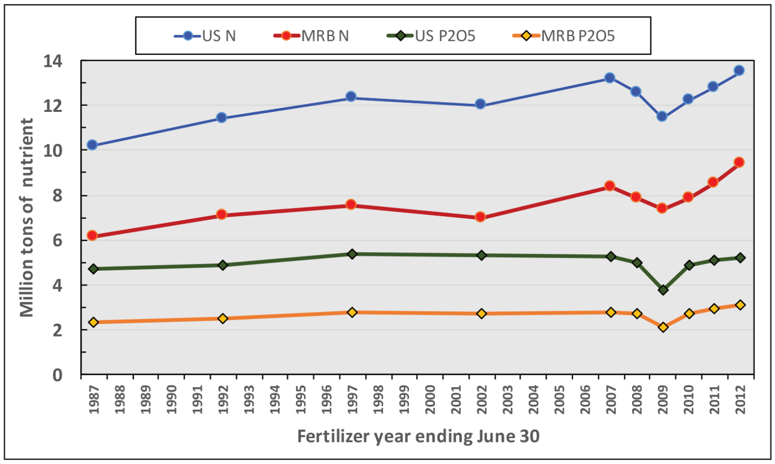

Figure 2. Consumption of fertilizer nitrogen (N) and phosphate (P_2O_5) within the Mississippi River Basin (MRB) from 1987 to 2012 constitutes a large portion of U.S. total consumption between 1987 to 2012. Source: AAPFCO, 2017; IPNI, 2012b.

Figure 3. (*left to right*) Mississippi River path through Louisiana; the "Old River" diversion of part of the flow into and through the Atchafalaya basin and into the Gulf of Mexico near Morgan City, Louisiana; and main stem Mississippi River flow into the Gulf of Mexico southeast of New Orleans, via the channelized birdfoot delta.

"The exclusion of sediments, freshwater, and nutrients of the Mississippi River from much of the coastal zone has eliminated a major land building and maintenance mechanism which historically counteracted many of the processes responsible for land loss and thus is a major factor in coastal land loss in Louisiana" (Day et al., 2000).

There are five major sub-basins in the MRB or MARB (**Figure 4**), and the Missouri sub-basin has the largest watershed drainage area (**Table 1**).

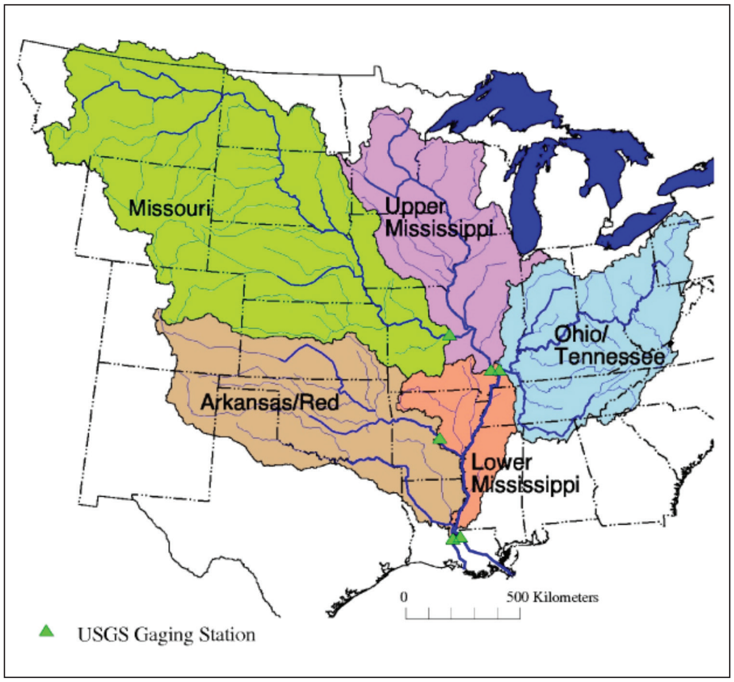

Figure 4. Five major sub-basins of the Mississippi River Basin and location of USGS gaging stations used to estimate sub-basin flow, nutrient concentrations, and loads. Source: Aulenbach et al. 2007.

Table 1. Five major sub-basins of the Mississippi River Basin and their drainage area compared to all U.S. cropland area and total land area.

Sub-basin	Drainage area			% of All Mississippi River Basin
	million acres	million hectares	km^2	
Missouri	334	135.3	1,353,300	43
Arkansas/Red	144	58.4	584,100	19
Ohio-Tennessee	130	52.6	525,800	17
Upper Mississippi	776	49.4	493,900	16
Lower Mississippi	45	18.3	183,200	6
Total Mississippi River Basin	**776**	**314**	**3,140,300**	**100**
U.S. Conterminous Land Area	**1,997**	**808**	**8,080,464**	
Total cropland area used for crop production	408	165	1,651,117	
Total crop, forage, pasture, and grazing land area	1,020	413	4,127,793	

Sources: https://toxics.usgs.gov/pubs/of-2007-1080/discussion_5large_basins.html; http://www.ers.usda.gov/data-products/major-land-uses/

The rate of water flow from the sub-basins into the Mississippi River mainstem and the northern Gulf of Mexico varies annually; which depends on the wide ranges in the amounts, intensity, and duration of precipitation, and the soil storage, crop consumptive water use, surface and subsurface drainage and hydrology, and other factors (**Figure 5**). The impacts of the 2012 drought that was felt in the Missouri, Upper

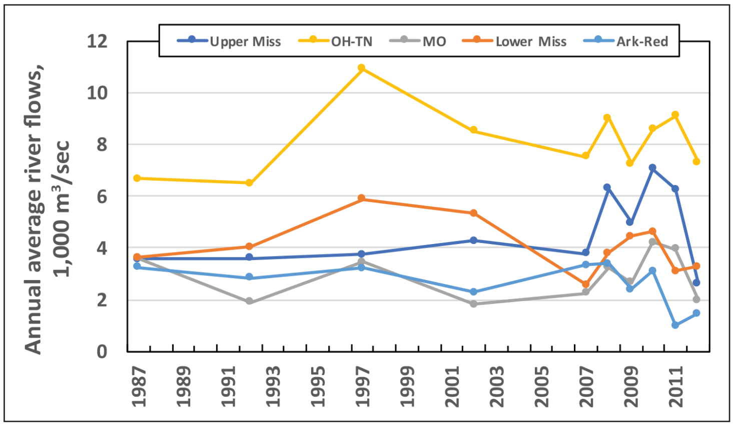

Figure 5. Annual average river flow rate differs among sub-basins of the Mississippi River watershed. Source: USGS, 2017.

Mississippi, and the Ohio-Tennessee sub-basins is evident in the flow trends. In addition, the record rainfall and flooding along the Ohio River in 1997 (http://www.weather.gov/lmk/flood97) is also clearly shown in the record of flow for the Ohio-Tennessee sub-basin.

The following graphic illustrates the relative volume of water discharged from different reaches of the MRB (**Figure 6**). By legislation, 30% of the combined Red River and Mississippi River mainstem flow is diverted westward via control structures, built and operated by the U.S. Army Corps of Engineers at what is known as the "Old River" site (EPA SAB, 2007; USACOE, 2009). That flow diversion site is near Point Breeze, Louisiana, which is about 120 miles upstream of New Orleans. That diverted flow enters the Red River channel and continues through the Atchafalaya Basin, to aid in providing flow relief, especially during flood events that could seriously threaten Baton Rouge, New Orleans, other downstream cities and lands.

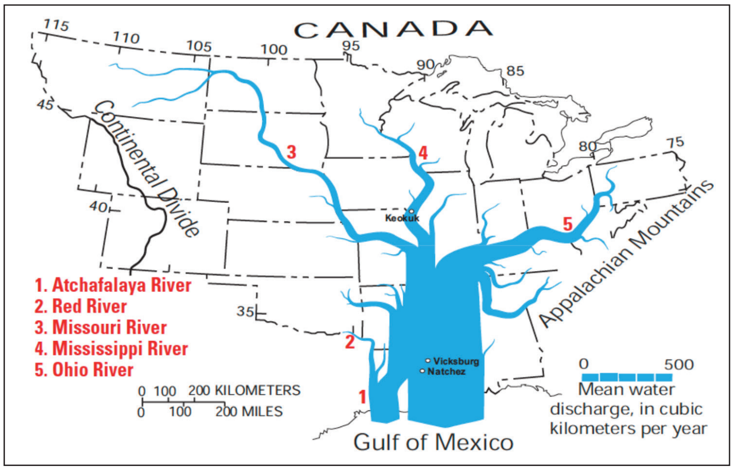

Figure 6. Relative sub-basin river water contributions to the Mississippi River flow, within different reaches of the Mississippi River Basin drainage; and the flow diversion through the "Old River" control structures, into the Atchafalaya Basin. Source: Milly, 2005; USGS, 2005.

How much N and P are being lost from farm fields and possibly making their way to the Mississippi River and the Gulf of Mexico; and what are the nutrient sources?

Nutrient delivery from different reaches of the MRB was estimated by USGS scientists in 2008, using SPARROW (**SPA**tially **R**eferenced **R**egressions **O**n **W**atershed attributes) modeling, which provided relatively gross estimates of loss for different geographies and crops (**Figures 7** and **8**). While fairly informative, those modeling approaches unfortunately did not consider any differences in soil characteristics or important nutrient management differences that affect both crop nutrient utilization and risks of nutrient loss; especially at the farm and field scales. More details on the USGS SPARROW model and nutrient flux and delivery to the Gulf of Mexico can be found at: https://water.usgs.gov/nawqa/sparrow/gulf_findings/faq.html. Those SPARROW watershed-scale modeling results, for the time period 1992-2002 and published in 2008, identified important sources of N and P delivery to the Gulf of Mexico, and pointed to corn and soybean croplands as dominating the annual nutrient loads (**Figure 8**).

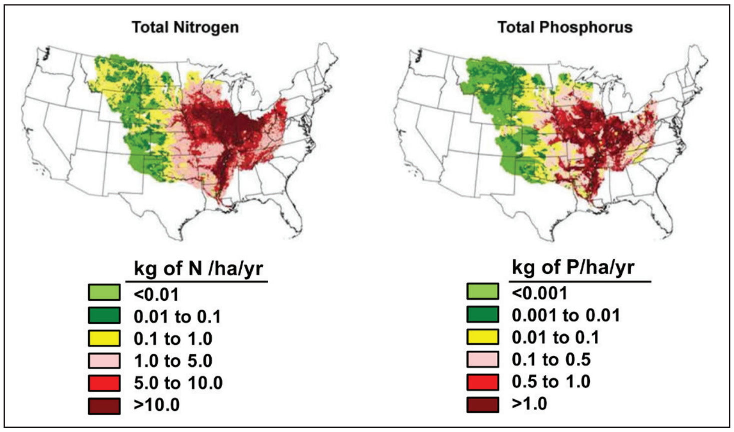

Figure 7. USGS SPARROW-modeled estimates of annual nitrogen and phosphorus loss and delivery from the Mississippi River Basin to the northern Gulf of Mexico. Adapted from Alexander et al., 2008.
Note: 1 kg/ha = 0.9 lb/A; 1 kg P = 2.3 kg P_2O_5

More detailed regional investigations of SPARROW-modeled nutrient loss from several river basins were undertaken by USGS and cooperating scientists, and the collection of results were published in a special issue of the Journal of the American Water Resources Association in 2011 (See Open Access articles in Volume 47, Number 5: http://onlinelibrary.wiley.com/doi/10.1111/jawr.2011.47.issue-5/issuetoc). More recently, a report on the SPARROW-modeled-estimates

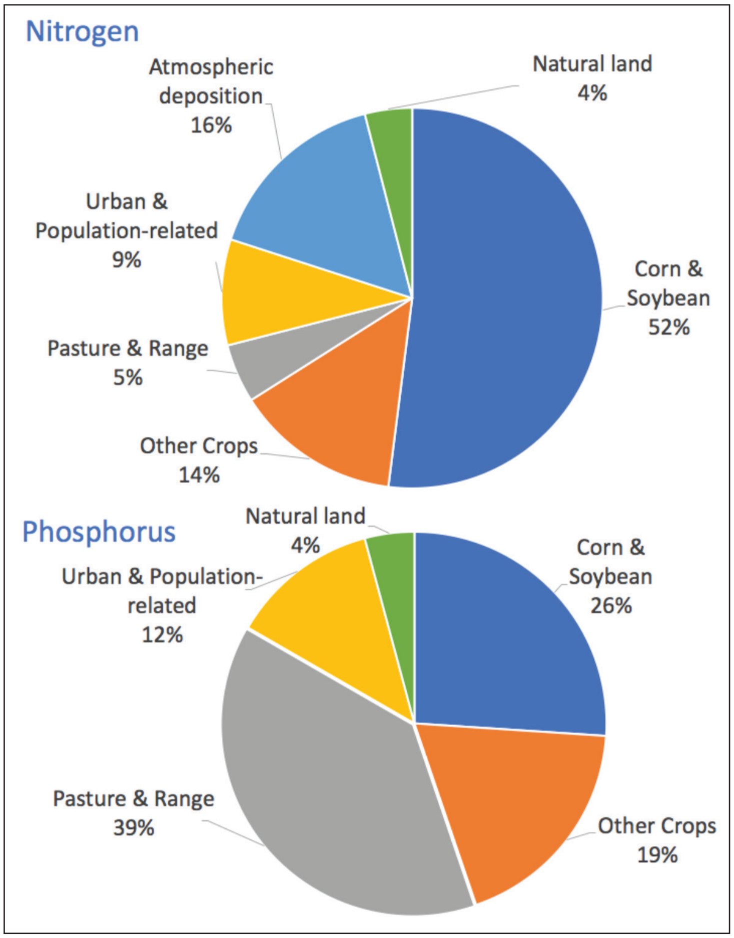

Figure 8. Estimated sources of nitrogen and phosphorus delivered to the northern Gulf of Mexico from the Mississippi River Basin, based on watershed-scale SPARROW modeling. **Source:** Alexander et al., 2008.

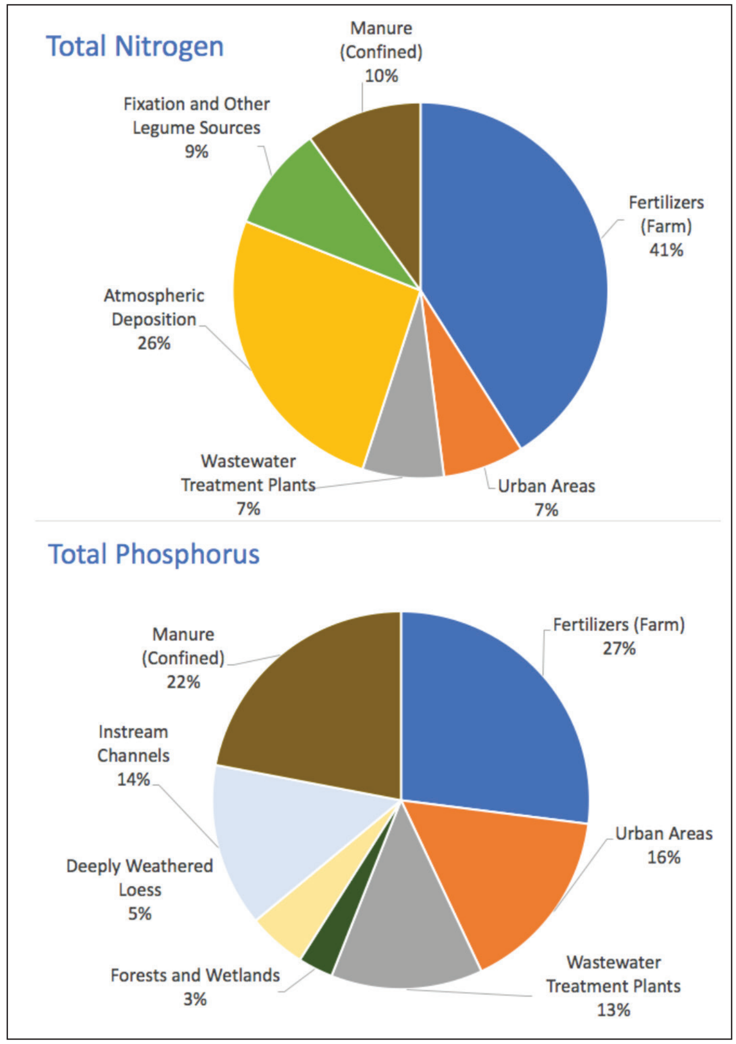

Figure 9. SPARROW-modeling identified fertilizer and manure contributions as prominent among other sources of nitrogen and phosphorus delivery to the northern Gulf of Mexico. **Source:** Robertson and Saad, 2013.

of the N and P losses delivered to the Gulf, identified specific nutrient sources, including estimates of fertilizer and manure contributions (**Figure 9**).

Although improvements continue to be made to the SPARROW model and other watershed-, farm-, and field-scale models, there are many questions that remain about the accuracy of the model-based estimates of nutrient losses from field edges in some geographies, for some cropping systems (Nangia et al., 2008). Monitoring of well-managed crop fields in Arkansas (Sharpley et al., 2016) showed edge-of-field N and P losses considerably lower than the loss rates calculated by the national and regional scale SPARROW models (Alexander et al., 2008; Rebich et al., 2011; and Robertson and Saad, 2013). For example, compare nutrient loss values in **Figure 7** above with **Table 2** below. When expressed as a portion of the applied nutrients, the measured (not modeled) losses of N and P from Arkansas farmer's fields ranged from 0.2 to 5.5%.

We would be remiss if we did not also mention that the USDA Natural Resources Conservation Service (NRCS) and partners have also conducted modeling work in the Conservation Effects Assessment Project (CEAP) to *"quantify the environmental effects of conservation practices and programs and develop the science base for managing the agricultural landscape for environmental quality"* (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/ceap/). Potter et al. (2006) and Johnson et al. (2015) overviewed some of the CEAP and related modeling results, which helped identify ongoing challenges and additional opportunities to refine conservation practice implementation across watersheds and farms.

Table 2. Two-year (2014 to 2015) average measured annual total nitrogen and total phosphorus loss in runoff from farmer fields in Arkansas is small, relative to the amount of nutrients added in fertilizer. Adapted from Sharpley et al., 2016.

Crop system	Location	Applied	Loss	Loss expressed as portion of fertilizer nutrient added
		- - lb/A/yr - -		%
Nitrogen				
Cotton	Dumas	110	6.1	5.5
Corn	Dumas	268	4.4	1.6
Corn	Atkins	120	1.7	1.4
Pasture	Elkins	150	0.3	0.2
Phosphorus				
Cotton	Dumas	42	1.9	4.5
Corn	Dumas	41	0.9	2.2
Corn	Atkins	22	0.5	2.3
Pasture	Elkins	50	0.1	0.2

Additional CEAP watershed project summaries are available online (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/ceap/ws/), and will not be summarized further here. As with the SPARROW modeling noted earlier, the CEAP modeling results have also estimated considerably greater N and P losses than those actually measured at farm field edges (**Table 2**), for the same specific soils and crops.

Models and monitoring of N and P losses from farm fields in the Mississippi River Basin are helpful, but are there other obstacles to reduced losses?

Modeling and monitoring can help identify opportunities for greater conservation practice adoption. However, the complexities involved in implementing effective educational programs that achieve farmer practice changes should not be underestimated. Osmond (2012) identified lessons learned from extension conservation outreach programs, which were based on Case Studies and CEAP modeling watershed experiences. Her noteworthy statements (Osmond et al., 2015) to summarize some of the social and cultural challenges to improved farmer adoption of sound nutrient management and conservation practices, included:

> *"A significant disconnect exists between farmer behavior relative to nutrient management and its importance as the first line of defense in reducing agricultural nonpoint-source pollution. Market forces on profits limit adoption, but failures of current policies to promote greater nutrient management are also a function of programs failing to understand and address social and cultural forces as identified in this paper. Understanding motivations for better nutrient use will require detailed key informant interviews that focus solely on farmer nutrient management decision-making."*

What are the MRB N and P losses and loads to the northern Gulf of Mexico; and has there been any reduction in loss since the 1980s?

The USGS measures water flow and nutrient concentrations regularly, in making monthly and annual (water years; beginning in October of prior year through September of reporting year) estimates of the combined N and P discharge from the Mississippi and Atchafalaya Basins (**Figure 3**). The USGS data are posted for public access (https://toxics.usgs.gov/hypoxia/mississippi/). Graphs of the USGS-estimated annual nutrient loads since 1980 show a trend for reduced annual total N loads, while total P loads reflect an increasing trend (**Figure 10**). Trends in nitrate-N and orthophosphate-P loads annually delivered to the Gulf since 1980, follow similar upward and downward trends as for total N and total P loads, respectively (**Figure 11**).

To determine if spring nutrient loads (April plus May) are reflecting trends similar to annual nutrient trends since 1980, we plotted those values, as shown in **Figures 12** and **13**.

The spatial variability in annual nutrient flux (loads) to different river systems is thought to be associated more

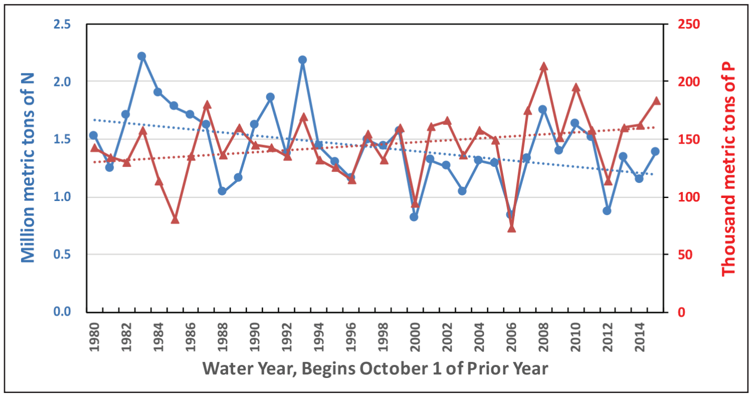

Figure 10. Annual loads of total nitrogen (N) delivered to the Gulf of Mexico from the Mississippi-Atchafalaya River Basin (MARB) since 1980 are trending downward, while loads of total phosphorus (P) are trending upward. **Source:** USGS, 2017.

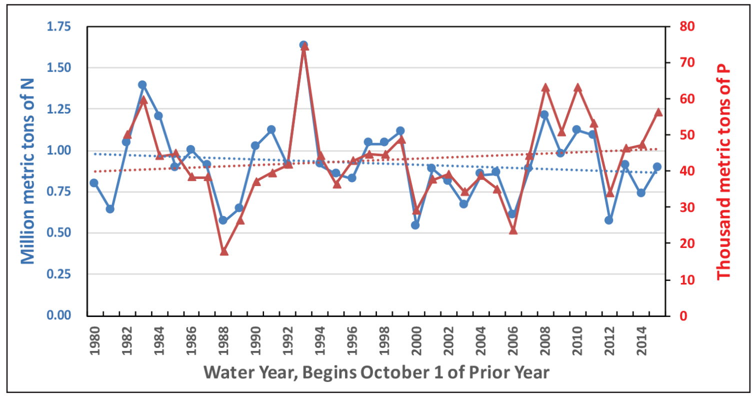

Figure 11. Annual loads of nitrate-N and orthophosphate-P delivered to the Gulf of Mexico from the Mississippi-Atchafalaya River Basin (MARB) since 1980 show declining and increasing trends, respectively. **Source:** USGS, 2017.

with nutrient inputs in watersheds, while the variability in nutrient flux among years (interannual variability) and the occurrence of extreme nutrient loading events are thought to be more associated with precipitation events; especially at the eight-digit hydrologic unit scale (Sinha and Michalak, 2016). Spring river flow and nutrient concentrations in the Mississippi River are usually greater than at other times of the year, and both peak in April and May (Greene et al, 2009). Spring flux of nutrients to the Gulf of Mexico, especially the combination of May river flow and nitrate-N load, was more strongly related to annual summertime hypoxia zone size from 1985 to 2007 than were annual nutrient loads. Greene et al. (2009) found that the combination of May nitrate-N flux (load), May water flow, and February total P flux explained 60 to 81% of the annual variation in the size of the Gulf of Mexico hypoxia zone, depending on the predictive model used to estimate nutrient loads from USGS river flow and nutrient concentration data.

What is hypoxia in the northern Gulf of Mexico, and is it reflecting any response to the changes in nutrient loads from the MRB?

Hypoxia is defined as 2 mg/L or less of dissolved oxygen primarily in the bottom waters, and is associated with accelerated phytoplankton (algal) and zooplankton growth. Organic matter from those “blooms” sinks to the bottom of the water column where it is decomposed by microorganisms, consuming available oxygen from the water column. Fish can leave a hypoxic area, but bottom dwelling organisms, which are less mobile, often cannot escape the hypoxia zone, may become stressed, and may die from oxygen deprivation.

The size of the summertime hypoxia zone in the relatively shallow waters (<100 m deep) along the Louisiana and Texas coast is measured annually with systematic cruises in mid-July by researchers with the Louisiana University

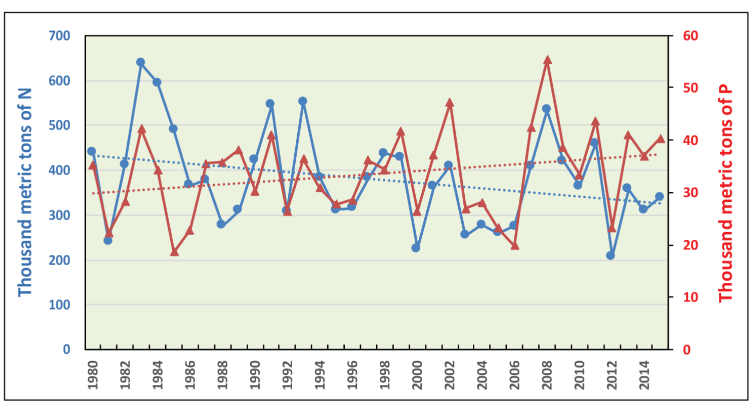

Figure 12. April plus May loads of total nitrogen (N) delivered to the Gulf of Mexico from the Mississippi-Atchafalaya River Basin (MARB) since 1980 are trending downward, while loads of total phosphorus (P) are trending upward. **Source:** USGS, 2017.

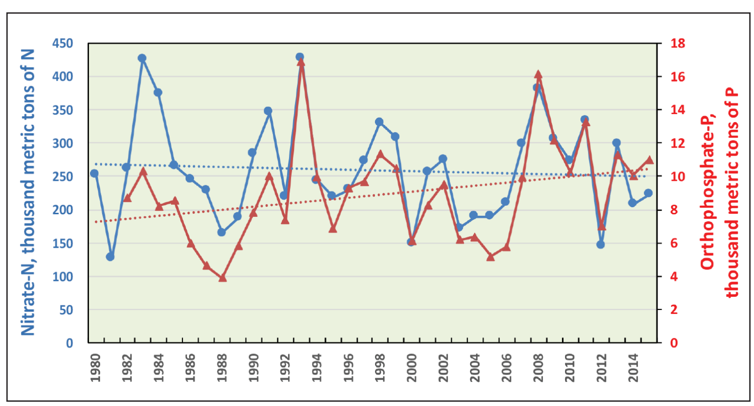

Figure 13. April plus May loads of nitrate-N delivered to the Gulf of Mexico from the Mississippi-Atchafalaya River Basin (MARB) since 1980 are trending downward, while loads of orthophosphate -P are trending upward. **Source:** USGS, 2017.

Marine Consortium (LUMCON), in cooperation with the National Oceanic and Atmospheric Administration (NOAA) (Rabalais et al., 2007 and 2010).

Although Gulf of Mexico hypoxia has been observed for more than 180 years, it has worsened since the mid-1950s, based on examination of sediment foraminifera (single-celled planktonic animals) records by Osterman et al. (2005). Periodic estimates of the size of the hypoxic zone occurred from 1975 to 1976, but consistent documentation of the spatial and temporal extent of Gulf of Mexico began in 1985, with funding from the NOAA National Ocean Service (https://gulfhypoxia.net/about-hypoxia/). Since those consistent annual Louisiana-Texas coastal water hypoxia cruises began, there has been better recognition that many interacting factors - in addition to increased nutrient loads and changes in nutrient concentration ratios - affect development and persistence of hypoxia: 1) stratification of warmer, fresh water over denser and cooler saline ocean water; 2) opposing (west to east) currents and strong winds (from the south and southwest) that can prevent or limit mixing of the Mississippi River water with ocean waters; 3) upwelling of nutrients from deeper coastal waters; and 4) erosional loss of nutrient-processing and sediment-accumulating abilities of coastal marshes (Bianchi et al., 2010: Dale et al., 2010; EPA SAB, 2007; Lehrter et al., 2013).

Changes in the ratio of dissolved silica (SiO_2) to N to P (atomic basis) are often used to assess the productivity and nutrient balance of aquatic systems, especially deep ocean waters. Klausmeier et al. (2004) pointed out that the canonical Redfield ratio of 16:1 for N:P *" … is not a universal biochemical optimum, but instead represents an average of species-specific N:P ratios."* Turner et al. (2007) investigated the total N to total P molar ratios (TN:TP), in the Mississippi River and observed that the TN:TP ratio had declined in recent decades, and ranged close to 20:1 from 1996 to 2004. He also found that the dissolved silica to nitrate atomic ratio, DSi:nitrate (or DSi:DIN) became close to the Redfield ratio of 1:1 in the later range of those years, indicating a growth limitation of diatoms. He also suggested that the phytoplankton growth in Mississippi River waters flowing into the Gulf is now more limited by N inputs than by P inputs. Increases in the N:Si and P:Si ratios may influence both the amounts and composition of phytoplankton, and result in potential shifts from diatoms

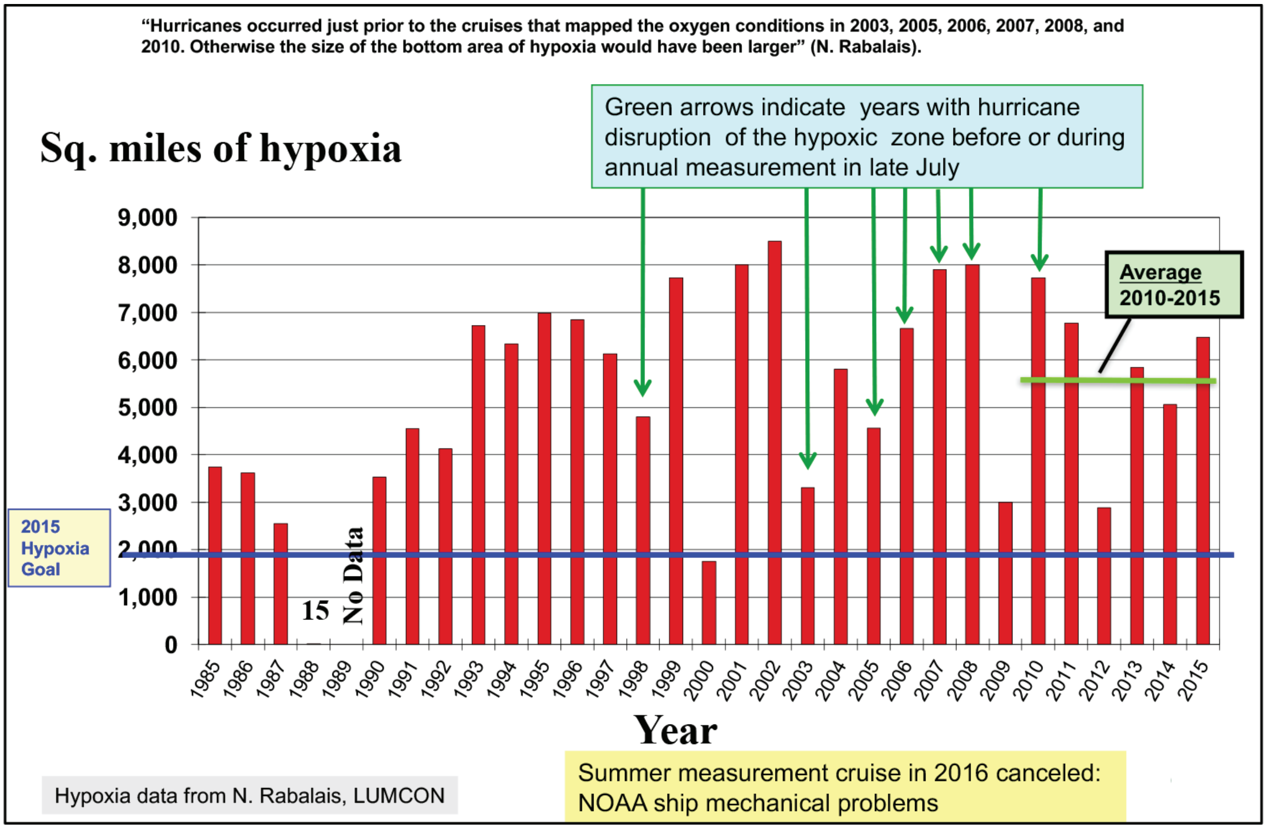

Figure 14. Annual summertime hypoxia (<2 mg/L dissolved oxygen) in the bottom waters of the northern Gulf of Mexico, 1985 to 2016. **Source:** Personal communication with N. Rabalais, LUMCON.

to flagellates and dinoflagellates (EPA SAB 2007; Dale et al., 2010). Managing both N and P losses to coastal waters has been argued as important to controlling both coastal and freshwater eutrophication (Conley et al., 2009c; Paerl, 2009).

Although referring to hypoxia in the Baltic Sea, the following statement by Conley et al. (2009a) is very relevant to hypoxia in the Gulf of Mexico:

> *"While we have a general understanding of nutrient biogeochemical cycles and the effects of hypoxia on those cycles, the effect of remediation efforts on the P, N, and SiO_2 biogeochemical cycles are only superficially understood with many basic questions remaining." "It is not enough to just understand the response of the ecosystem to nutrient and climate forcing. We also need to quantify the effects of nutrient load reductions for different scenarios. Even if nutrient source discharges on land are stabilized at present levels, nutrient loading will continue to increase due to the slow transport and reversible mass transfer processes in the inland subsurface water system (soil, groundwater, stream and lake sediments), where much of the anthropogenic nutrient source inputs still reside" (Conley et al., 2009b).*

It may take decades or longer to observe desired changes in water quality associated with nutrient losses and complex interactions in very large watersheds. Because of that lag effect, it is important to select *"appropriate indicators with which to assess progress"* and to design *"effective monitoring programs to detect water quality response and document effectiveness."* Such planning and action can help determine when and how water quality may respond to changes in land and nutrient management, and if conditions truly are improving (Meals et al., 2010).

Since 1985, the measured areal extent of the northern Gulf of Mexico summertime hypoxic zone has varied, with no clear trends upward or downward (**Figure 14**); but periodic declines due to drought-related reduced water flow and nutrient discharges, coastal current and wind factors, and periodic hurricanes. Droughts were experienced in 1988, 2000, and 2012 in much of the central portion of the MRB, and lower hypoxia areas were clearly observed in those years; emphasizing the impacts of water flow and the attendant nutrient loads on hypoxia development.

What are the current goals and actions to shrink the size of the hypoxic zone in the Gulf of Mexico, and to reduce nutrient losses from the MRB?

Goals and action plans to reduce hypoxia, and to coordinate nutrient loss reduction, have been established within the MRB by cooperating federal and state agencies (**Figure 15**).

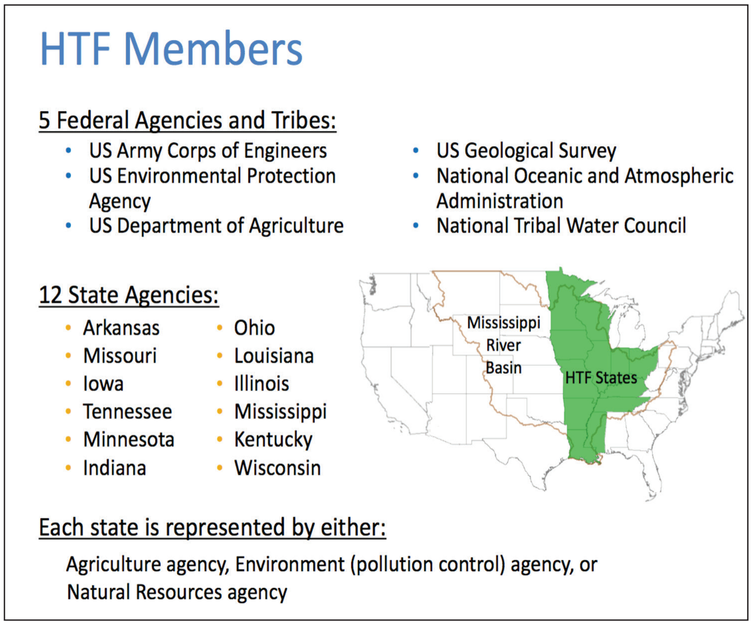

Figure 15. Coordination of Gulf of Mexico hypoxia and nutrient loss reduction is a shared responsibility among federal and state agencies, referred to as the Hypoxia Task Force (HTF). **Source:** Personal communication with Dr. Ellen Gilinsky, U.S. EPA, 2015.

The federal and state agency Hypoxia Task Force (HTF; https://www.epa.gov/ms-htf) Report to Congress in 2015 (https://www.epa.gov/ms-htf/hypoxia-task-force-2015-report-congress) stated:

> *"The federal members of the HTF issued a unified federal strategy in September 2013 to guide assistance to states and continued science support."*
>
> *In May 2014, " ... the HTF entered into an agreement with 12 land grant universities (LGUs) to reduce gaps in research and outreach/ extension needs in the Mississippi/Atchafalaya River Basin (MARB)."*
>
> *"In 2006, EPA asked its Science Advisory Board (SAB) to evaluate the most recent science on the Gulf hypoxic zone, as well as potential options for reducing the size of the zone. The SAB's report*

(USEPA, 2007) reaffirmed that the hypoxic area in the Gulf is caused primarily by nutrient loads from the MARB, and indicated that significant reductions in both nitrogen and phosphorus are needed. The report states that in order to achieve the coastal goal for the size of the hypoxic zone and improve water quality in the MARB, a dual nutrient strategy targeting at least a 45 percent reduction in both riverine total nitrogen load and in riverine total phosphorus load is needed."

"The 2008 Action Plan calls for a reassessment, in five years, of the HTF approach to addressing excess nitrogen and phosphorus loads in the MARB and reducing the size of the Gulf hypoxic zone. The 2013 Reassessment reaffirms the HTF's commitment to implementing the 2008 Action Plan and provides a snapshot of progress to date (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2013)."

"Given the size of the MARB and the Gulf, the many actions that need to be funded and implemented, the reservoir of excess nutrients in soils and groundwater, and the impacts of climate change (e.g., more intense and frequent rain storms leading to more nutrient runoff and warmer waters which are not able to hold as much dissolved oxygen), the HTF recognized that it will take additional time to meet the water quality goals in those large bodies of water."

The most current (and revised) HTF hypoxia and MARB (MRB) goal statement now reads as follows:

"We strive to reduce the five-year running average areal extent of the Gulf of Mexico hypoxic zone to less than 5,000 square kilometers (1,930 mi2) by the year 2035. Reaching this final goal will require a significant commitment of resources to greatly accelerate implementation of actions to reduce nutrient loading from all major sources of nitrogen and phosphorus in the Mississippi/Atchafalaya River Basin (MARB). An Interim Target of a 20% reduction of nitrogen and phosphorus loading by 2025 (relative to the 1980-1996 average MARB loading to the Gulf) is a milestone for immediate planning and implementation actions, while continuing to develop future action strategies to achieve the final goal through 2035. Federal agencies, States, Tribes and other partners will work collaboratively to plan and implement specific, practical and cost-effective actions to achieve both the Interim Target and the updated Coastal Goal."

Agricultural, pollution control, and natural resource agencies in the 12 states along the central portion of the MRB (**Figure 15**), were also charged with developing

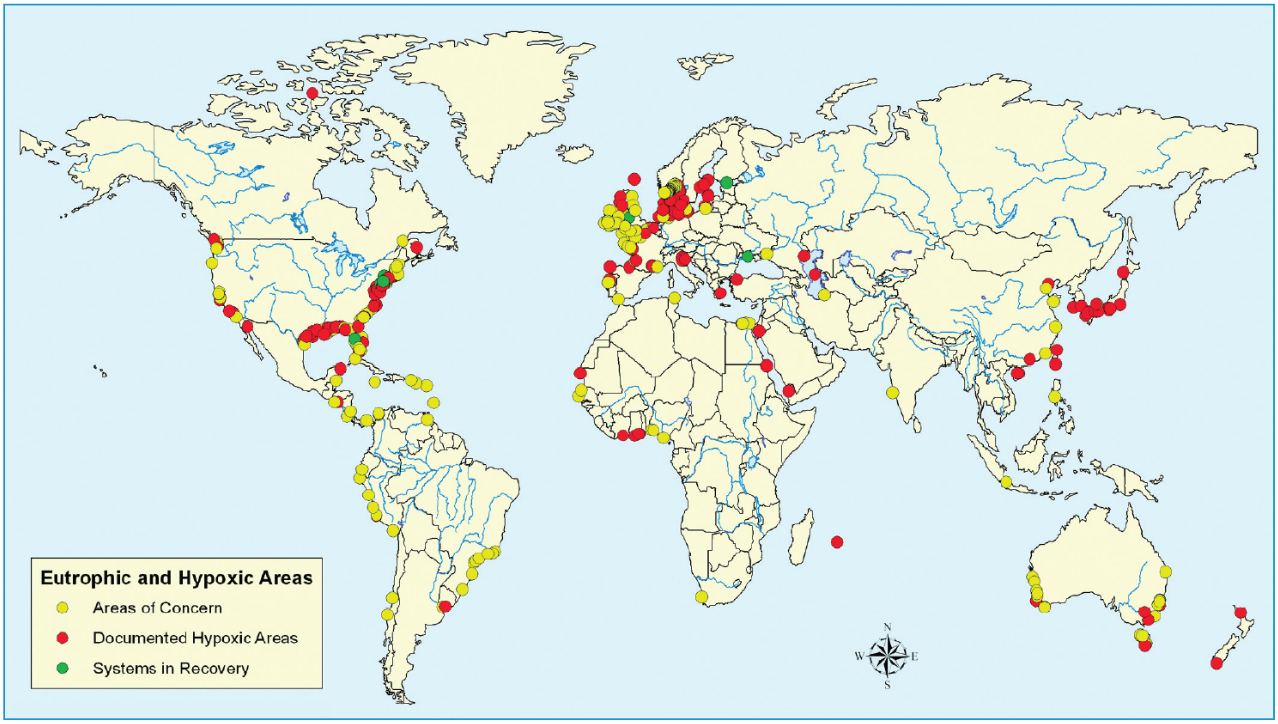

Figure 16. Locations of documented hypoxia and eutrophication in coastal waters around the world. Source: Selman et al., 2008.

state nutrient loss reduction strategies by 2013; with an aim to assess nutrient delivery to local waterways, improve local water quality, and to reduce losses that contribute to Mississippi River loads and their eventual delivery downstream to the Gulf of Mexico (https://www.epa.gov/ms-htf/hypoxia-task-force-nutrient-reduction-strategies).

Is hypoxia only occurring in the U.S.?

Hypoxia is a world-wide problem, and not just a U.S. water quality challenge. More than 550 locations with coastal hypoxia and/or eutrophication have been identified globally (Diaz and Rosenberg, 2008; Selman et al., 2008; **Figure 16**).

What are the economic impacts of hypoxia on Gulf of Mexico fisheries?

The annual commercial value of Gulf of Mexico fisheries was estimated at $670 million by NOAA in the EPA SAB (2008) report. A more recent overview for the 2003-2006 monitoring period (EPA, 2012) showed:

> *"The top commercial species are invertebrate species of white, brown, and pink shrimp. These species accounted for over $350 million in 2006 alone. From 2003 to 2006, Eastern oyster catches provided over $240 million, and blue crab generated $165 million for commercial fisheries. The menhaden fishery generated $165 million from 2003–2006 from approximately 400,000 metric tons per year (NMFS, 2010). Interestingly, and unlike most other Gulf fisheries, the menhaden catch far exceeded its market value. Menhaden are used in a variety of industries such as fertilizer production, protein in animal feed, and flavoring in pet foods."*

Gulf of Mexico fisheries are among the most productive in the world, with annual production (yield) of finfish, shrimp, and shellfish exceeding that of the South and mid-Atlantic, Chesapeake, and New England areas of the U.S. combined (Shepard et al., 2013). The U.S. Gulf of Mexico states have four of the top seven fishing ports in the U.S. by weight, and eight of the nation's top 20 fishing ports in dollar value. About 78% of the total U.S. shrimp landings, 62% of the U.S. total oyster landings, and 16% of the U.S. total commercial fishery landings from 2007 to 2009 were from the Gulf of Mexico region. The annual number of pounds of commercial fishery landings from the region over that same time period exceeded an annual value of $660 M. The Gulf of Mexico also accounted for more than 44% of all U.S. marine recreational fish catching in 2009. Over $474 M worth of commercial shellfish were harvested in the Gulf of Mexico's coastal wetlands in 2009 (NOS, 2011). There are 37 major U.S. coastal estuaries along the Gulf of Mexico, and 16 (43%) have been reported to experience nutrient-related water quality problems.

While nutrient delivery from fresh waters to coastal waters can be beneficial to a point, excessive nutrient loading, eutrophication, lack of mixing and flushing of the waters, and hypoxia development can contribute to losses of fisheries, losses in biodiversity, and alteration of the food webs (Diaz, 2001). Unlike other hypoxia zones around the globe, Gulf of Mexico hypoxia had not experienced a decline in fishery production associated with hypoxia-induced mortality, according to Diaz (2001; **Table 3**).

Table 3. Ecological and economic effects of hypoxia near the Louisiana shelf in the northern Gulf of Mexico compared with similar human-affected hypoxic zones around the world. Adapted from Table 2 in Diaz, 2001.

System	Affected area, km^2	Benthic (*bottom water*) response	Benthic recovery	Fishery response
Louisiana Shelf, U.S. Gulf of Mexico	15,000	mortality	annual	Stressed but still highly productive; mortality reported in shallow water related to "Jubilees".
Kattegat, Sweden-Denmark	2,000	mass mortality	slow	Collapse of Norway lobster, reduction of demersal fish. Hypoxia prevented recruitment (*entry and survival*) of young lobsters.
Black Sea Northwest Shelf	20,000	mass mortality	annual	Loss of demersal (*living in and feeding near the bottom*) fisheries, shift to planktonic[1] (*small and microscopic which float or swim weakly*) species.
Baltic Sea	100,000	eliminated	none	Loss of demersal fisheries, shift to planktonic species. Cod recruitment impaired.

[1]Organisms that float and drift are an important food source for fish and other animals. Planktonic algae are fed upon by microscopic animals called zooplankton, which are fed upon by shrimp, crab, and fish; affecting the entire ocean food web.

There are no fish or shrimp quantity data that consistently indicate impacts of annual hypoxia in the Gulf of Mexico. Zimmerman and Nance (2001) reported negative hypoxic zone effects on brown shrimp catch off the coasts of Louisiana and Texas from 1985 to 1998, but did not observe any relationship with the white shrimp catch. Extending that work, a later report cited a significantly negative correlation of hypoxic zone size and the combined Louisiana and Texas coast catch of brown shrimp from 1985 to 2004, no significant effects on brown shrimp catch off the Louisiana coast alone, and no significant impacts on white shrimp catch off either coasts (O'Connor and Whitall, 2007).

Although the Gulf of Mexico produces 78% of the U.S. shrimp landings, 80% of the shrimp consumed in the U.S. are imported. Annual hypoxia effects on Gulf of Mexico shrimp landings, and supply-and-demand price responses are complex and confound direct "cause and effect" analyses. Buyers may supply local and national consumer demands from imports, if Gulf shrimp supplies are short; or if shifts occur in the shrimp size and quantity, that cyclically affect local and international markets and prices. In spite of these market complexities, an investigation was recently undertaken on whether the ecological impact of hypoxia decreases the quantity of large shrimp relative to small shrimp, using a time series of the increase in the price of large shrimp relative to small shrimp. Although Smith et al. (2017) reported some causal effects of Gulf of Mexico hypoxia on shrimp markets and prices, their summarizing statements below are noteworthy:

"The naive quantity-based analysis shows some evidence that contemporaneous hypoxia increases the catch of large shrimp but no evidence that contemporaneous hypoxia affects overall shrimp catch and no evidence of long-term impacts of hypoxia on shrimp catch."

"We provide evidence that hypoxia causes economic effects on a major fishery that was once the most valuable fishery in America."

"Our analysis is also a breakthrough in causal inference for coupled human-natural systems. Although establishing causality with observational data is always challenging, feedbacks across the human and natural systems amplify these challenges and explain why linking hypoxia to fishery losses has been elusive. We offer an alternative approach using a market counterfactual that is immune to contamination from feedbacks in the coupled system. Natural resource prices can thus be a means to assess the significance of an ecological disturbance."

"Our results are an important step toward quantifying the economic value of reduced upstream nutrient loading in the Mississippi Basin and are broadly applicable to other coupled human-natural systems."

Are the N and P balances of agricultural croplands within the MRB changing, and reflecting any potential for improved nutrient utilization, retention and reduced losses?

The International Plant Nutrition Institute (IPNI) developed a Nutrient Use Geographic Information System (NuGIS; IPNI, 2012b) to help inform agriculture (and the public) on nutrient balances and other similar metrics across the U.S. As explained by Fixen et al. (2012), NuGIS relies on *"county-level estimates of N, P and K (potassium) applied to the soil in fertilizer and livestock manure, and removed by harvested agricultural crops. Geospatial techniques are used to estimate balances for 8-digit hydrologic units using the county-level data."* Estimates are made for five years, coinciding with the USDA Agricultural Census years from 1987 to 2007, and annual updates have been developed for 2008 to 2012. The fundamental approach used in NuGIS to estimate partial nutrient balances is shown in **Figure 17** for N. A similar partial balance approach is used for P, except biological fixation (capturing N_2 gas from the air and synthesizing it into the

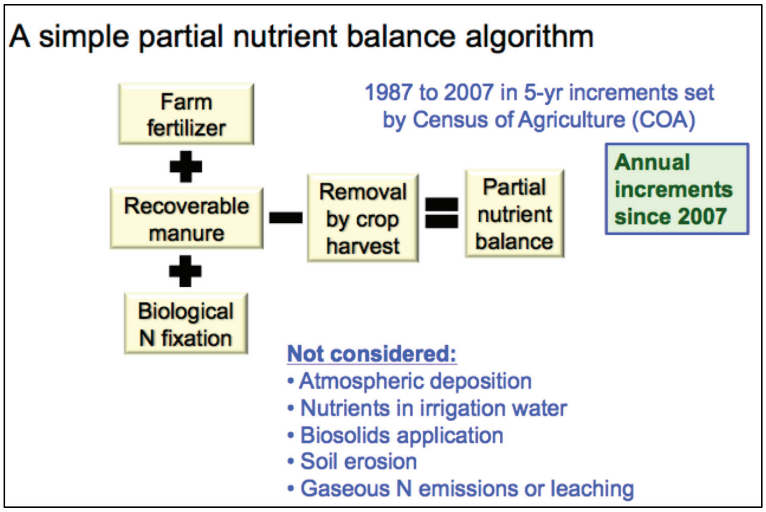

Figure 17. Basic model for simple partial nutrient balance (or net balance) used in NuGIS, with nitrogen as the example. Adapted from P.E. Fixen et al., 2012.

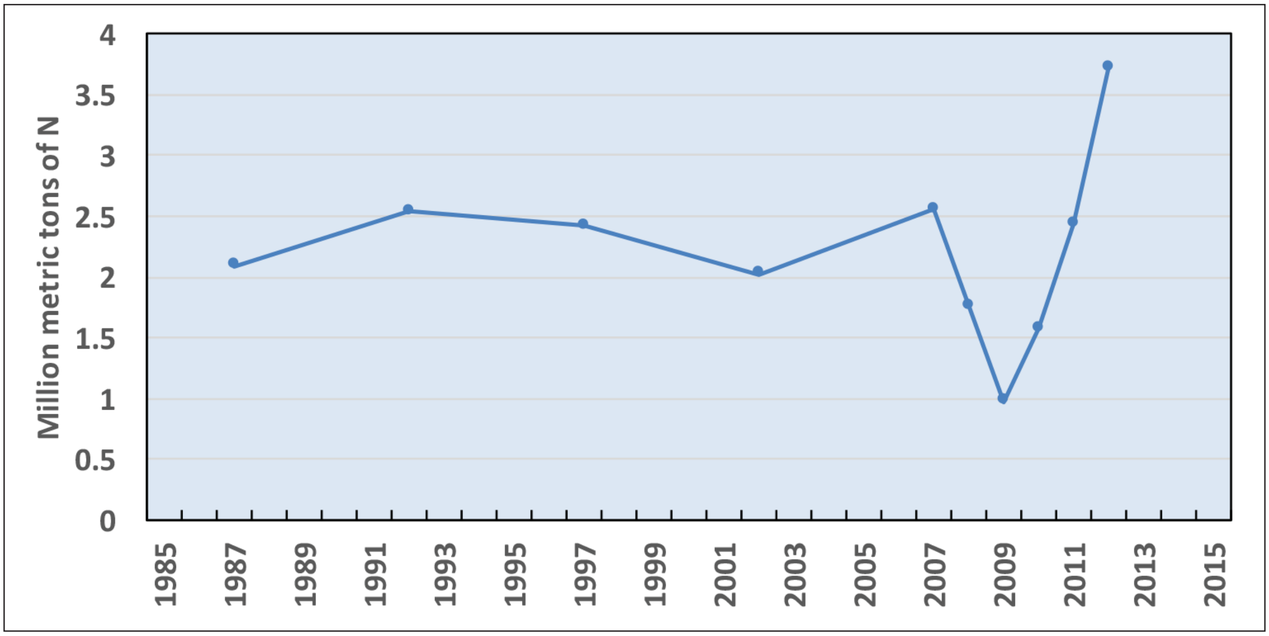

Figure 18. Cropland partial N balance (net balance) in the Mississippi-Atchafalaya River Basin from 1987 to 2012. **Source:** NuGIS; IPNI, 2012b.

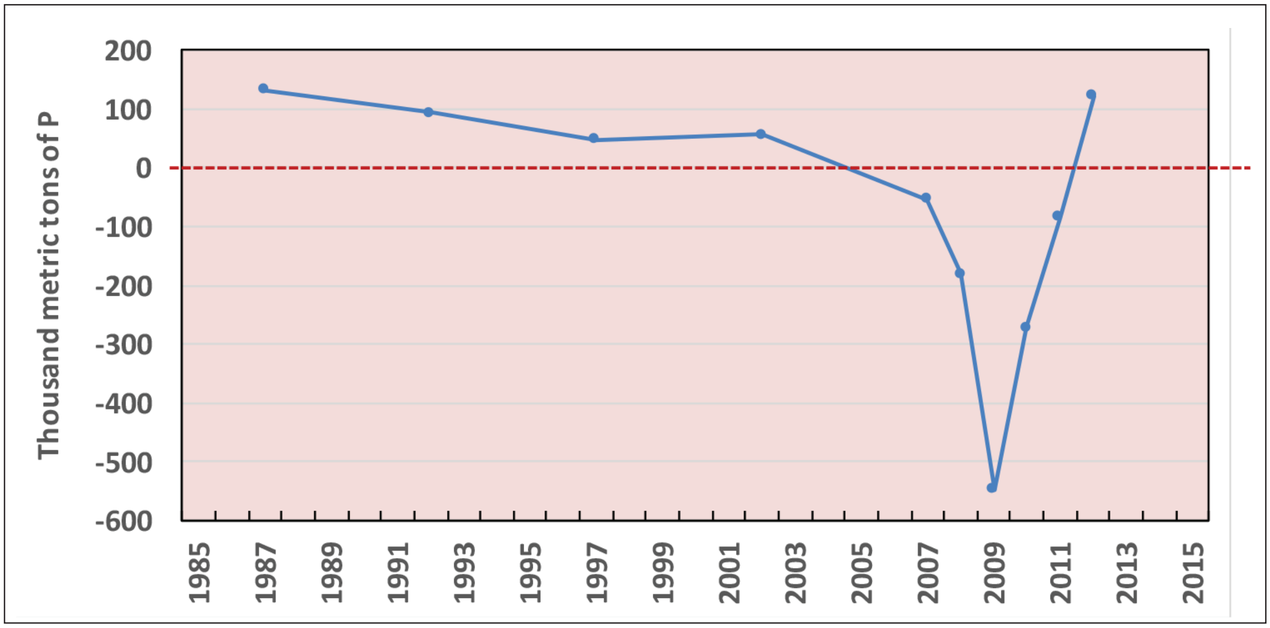

Figure 19. Cropland partial P balance (net balance) in the Mississippi-Atchafalaya River Basin from 1987 to 2012. Source: NuGIS; IPNI, 2012b. Red dashed line represents balance between inputs and crop harvest removal. As was noted by Fixen et al. (2012), *"Care needs to be used in interpreting national figures on nutrient balance due to the great variability existing among regions within the U.S."* Partial N balances for the five major sub-basins of the MRB are shown in **Figure 20**, and the partial P balances (net balances) are shown in **Figure 21**.

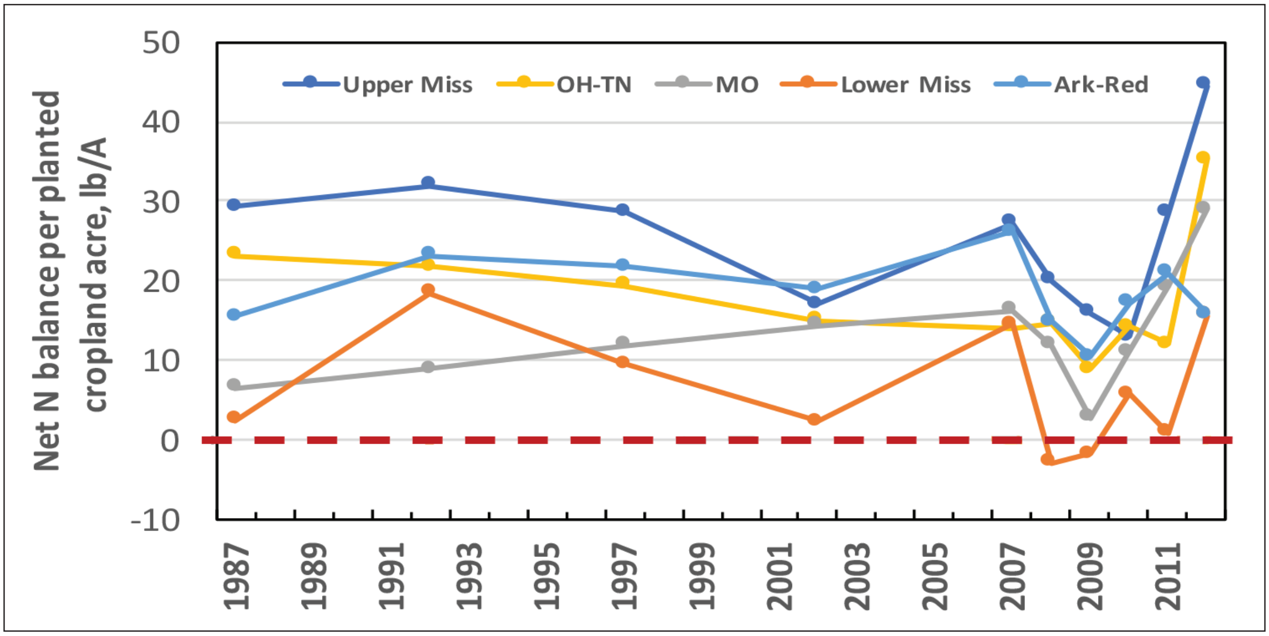

Figure 20. Cropland partial nitrogen balance (Net N balance) from 1987 to 2012 in the five major sub-basins of the Mississippi-Atchafalaya watershed. Note: MRB sub-basins are: Upper Miss = Upper Mississippi River, OH-TN = Ohio-Tennessee, MO = Missouri, Lower Miss = Lower Mississippi, Ark-Red = Arkansas-Red. Red dashed line represents balance between inputs and crop harvest removal. **Source:** NuGIS; IPNI, 2012b.

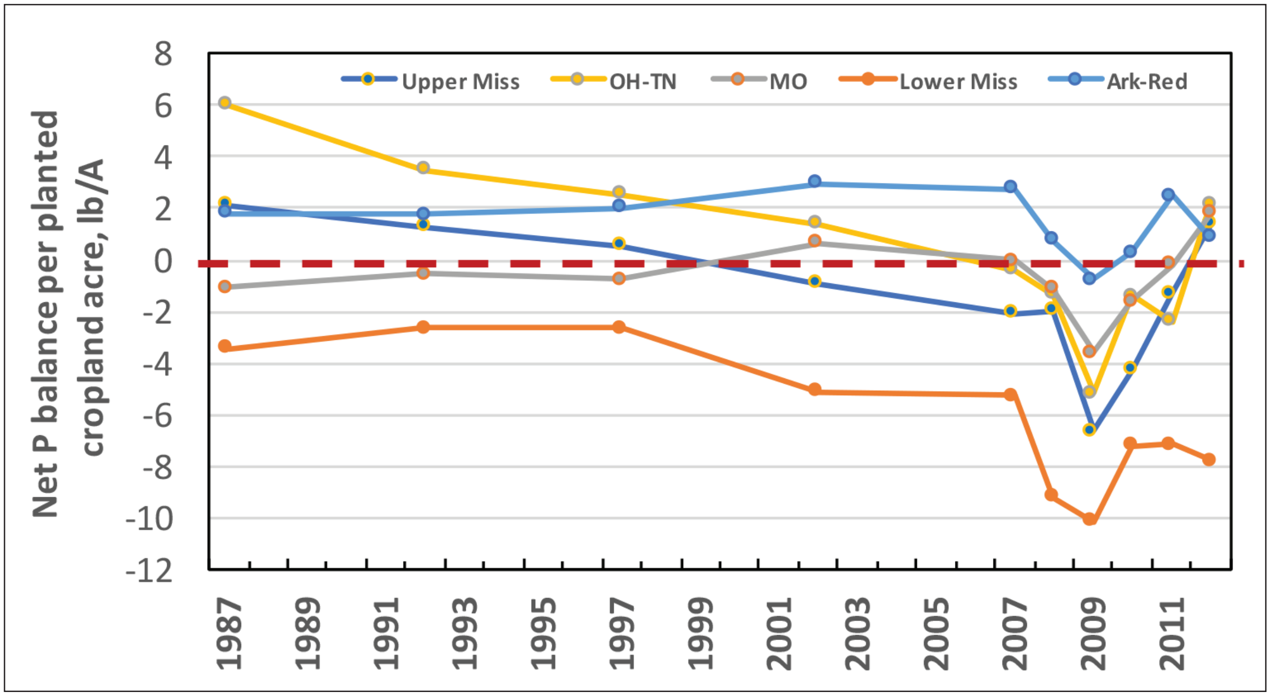

Figure 21. Cropland partial phosphorus balance (Net P balance) from 1987 to 2012 in the five major sub-basins of the Mississippi-Atchafalaya watershed. Note: Red dashed line represents balance between inputs and crop harvest removal. **Source:** NuGIS; IPNI, 2012b.

tissues of plants) is not a factor nor considered.

In this paper, we relied on NuGIS to develop summary data for the MRB (or MARB) croplands to investigate trends in agricultural cropland nutrient performance from 1987 to 2012 (IPNI Scientists, 2014). **Figure 18** shows a relatively flat trend in partial N balance for harvested cropland in the MRB across the years, but the effects of drought in 2012 in much of the upper to central U.S. Midwest can be easily seen. In addition, the impacts of rising global and U.S. feed and fertilizer prices from 2007 to 2009 (http://usda.mannlib.cornell.edu/usda/nass/AgriPric//2000s/2008/AgriPric-08-29-2008.pdf) were reflected in declines in fertilizer nutrient consumption in those years (**Figure 2**), and also in the partial N balance trend shown in **Figure 18**. A similar trend and pattern over time is shown in **Figure 19** for P, except that the partial P_2O_5 balance for cropland is negative in many years; indicating that P removal with crop harvests was greater than P inputs applied to the soils and cropping systems as fertilizer and recoverable manure.

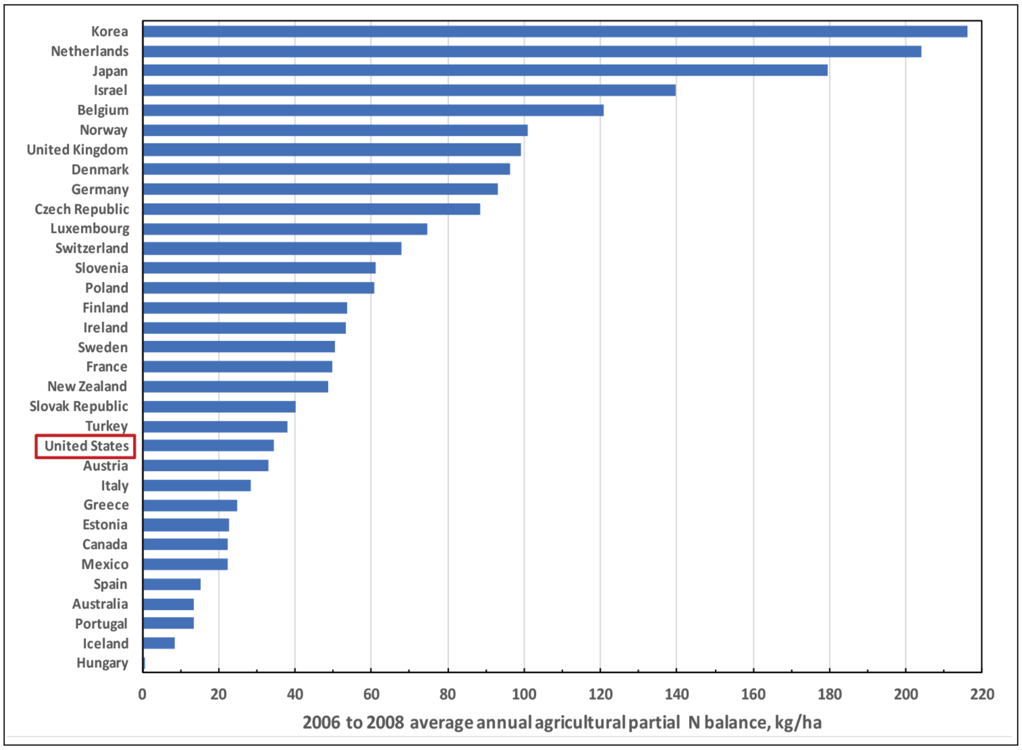

Figure 23. Annual agricultural partial N balance, averaged from 2006 to 2008, for different countries; using a net N balance estimation method similar to the method used in NuGIS (IPNI, 2012b). Note: 1.12 kg/ha = 1 lb/A. **Source:** OECD, 2013.

What are the fertilizer and manure consumption trends, compared with the crop harvest removal N and P trends in the Mississippi-Atchafalaya Basin?

Comparison of the amount of N removed in crop harvests in the MRB from 1987 to 2012 shows that harvest removal values have been relatively close to the combined fertilizer and recoverable manure inputs, such that the

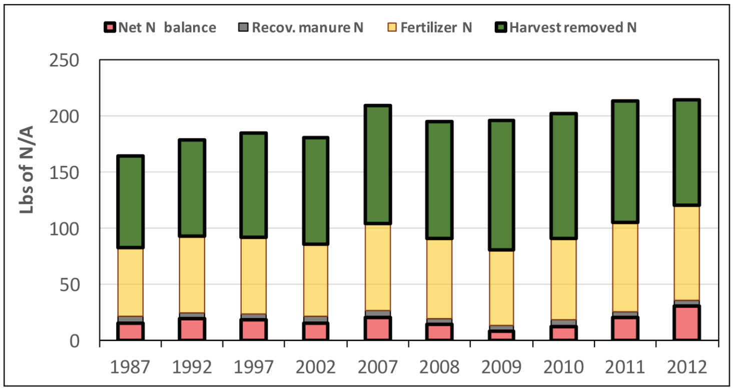

Figure 22. Mississippi-Atchafalaya watershed (MRB) fertilizer and recoverable manure nitrogen (N) inputs, crop harvest removals and net balance (partial balance) for croplands from 1987 to 2012. Notes: X-axis is simplistic, and may visually distort actual time spans: See Figures 20 and 21. 1 lb/A = 1.12 kg/ha. Source: NuGIS; IPNI, 2012b.

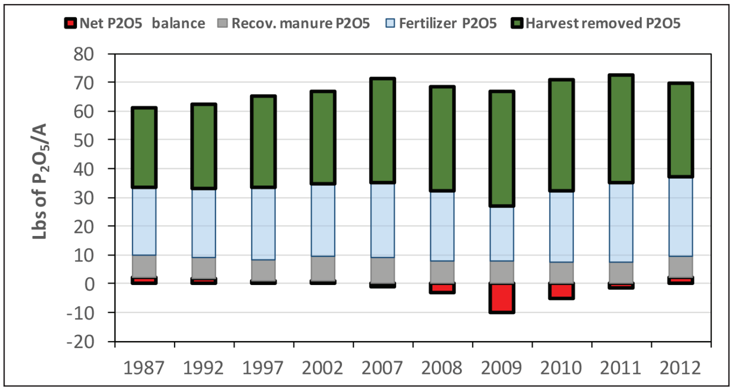

Figure 24. Mississippi-Atchafalaya watershed (MRB) fertilizer and recoverable manure P_2O_5 inputs, crop harvest removals and cropland net balance (partial balance) from 1987 to 2012. Note: X-axis is simplistic, and may visually distort actual time spans: See Figures 20 and 21. 1 lb/A = 1.12 kg/ha; multiply lb P_2O_5/A values by 0.44 to adjust to lb of P/A. Source: NuGIS; IPNI, 2012b.

net N balance (partial N balance) per cropland acre has generally been below about 20 lb/A (22 kg/ha); except for the Midwest drought year of 2012 (**Figure 22**). The U.S. cropland partial N balances have been markedly lower than the partial N balances (which are determined by methods similar to NuGIS methods) observed in many other countries around the world (**Figure 23**; also compare with **Figure 20**) (OECD, 2013; Cavigelli et al., 2012).

Crop harvest removal of P in the MRB (**Figure 24**) has frequently exceeded fertilizer plus manure inputs, and has resulted in negative P balances for many years. Continued negative partial P balances (net P balances) pose risks of declines in crop production, where plant nutrition needs are neglected, and can result in depleted soil P fertility; a serious threat to long-term sustainability.

Are these MRB N and P balances and trends consistent with recent national soil test summary data and soil fertility changes, reported by IPNI?

The most recent summary report on North American soil test levels (IPNI, 2015) covered a snapshot of 2015 soil test levels, but also addressed data spanning 15 years from three previous summaries by the Institute. That 2015 IPNI soil test summary report included P tests on more than 7.5 million soil samples, and showed some significant shifts in soil test P levels in recent years, which are in relative agreement with some of the partial (or net) P balance changes mentioned above (Fixen et al., 2015). The authors of that IPNI (2015) soil test summary report stated: *"Over the period 2001 to 2015, North America data indicate fewer samples testing higher in P and more samples testing lower."* More specifically, they reported: "When considered as a whole, North America saw increases in the percent of samples testing in the lower categories ranging from 0 to 20 ppm Bray and Kurtz P1 equivalent. Decreases were observed in the higher categories—those 21 ppm and above."

There are no national summaries of soil testing for N (total, ammonium, nitrate, or available) in North America because the many different forms of N in the soil are dynamic and under a constant state of change, largely because of diverse soil microbial activity. *"While residual N has proven to be a useful index in certain regions of the U.S., no generally accepted index exists for N mineralization"* (Follett, 2001).

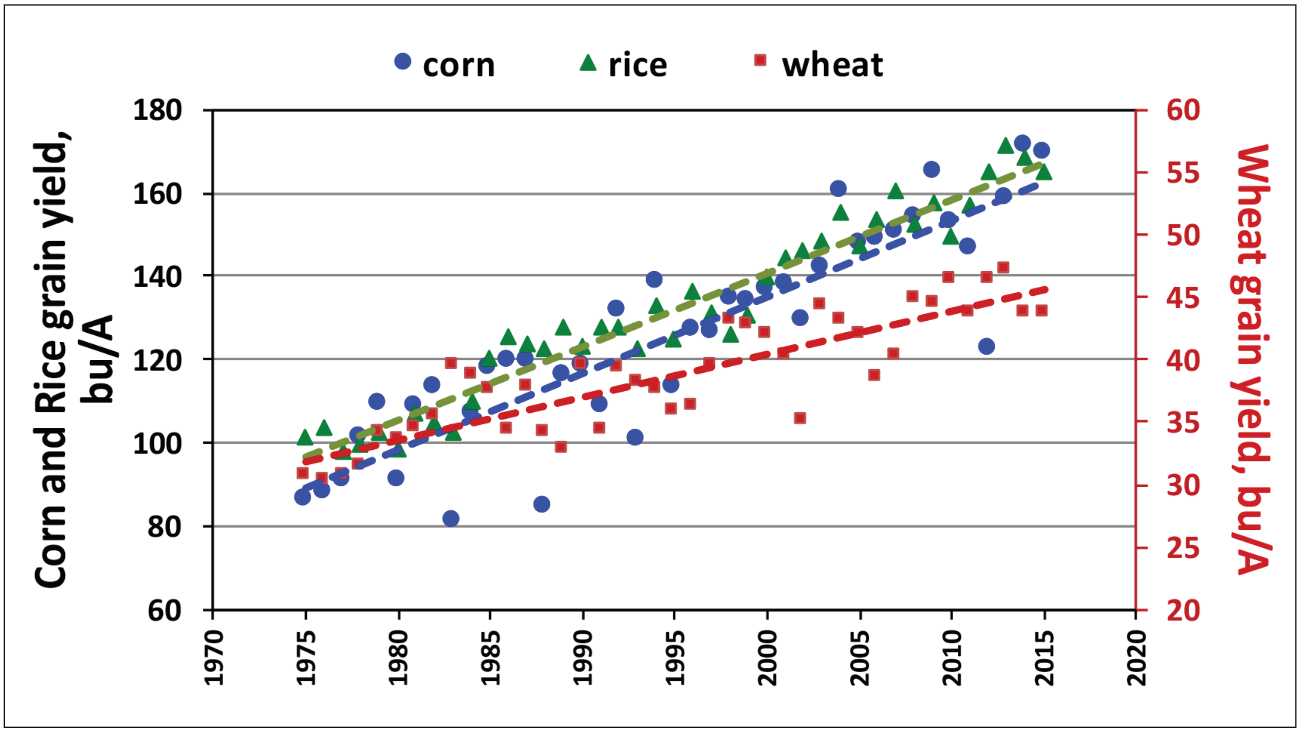

Figure 25. Yields of major cereal grain crops in the U.S. trended strongly upward from 1975 to 2015. Note: Wheat yields (bu/A) shown on secondary Y-axis at right, to illustrate a more balanced comparison of yield change among the three crops. **Source:** NASS, 2017.

What are the U.S. major crop yield trends?

The grain yields of three major cereal crops in the U.S. are shown in **Figure 25**. As was noted earlier, the farms in the MRB represent >90% of this U.S. crop production. Continued increases in crop yields, when combined with wise soil and water conservation practices and site-specific 4R nutrient management (IFA, 2009; IPNI, 2012a), may help to maintain an appropriate agronomic-economic-environmental nutrient balance, and contribute to reductions in losses of N to water resources. For example, higher crop yields and greater crop harvest N removal, coupled with modest rates of change in N inputs in recent years, contributed to a lower N balance in the Illinois River watershed in Illinois and reduced stream flow-weighted nitrate-N concentrations in the Illinois River (McIsaac et al., 2016).

Conclusion

It is encouraging to see the trends in reduced annual (and also spring) nitrate-N and total N loads in the Mississippi River, which are delivered to the northern Gulf of Mexico each year. As site-specific, optimized 4R nutrient management (Bruulsema, 2017; Snyder, 2016) is more widely implemented in the Mississippi River Basin (MRB) - in concert with appropriate and complementary in-field and edge-of-field soil and water conservation practices (Christianson et al., 2016; Delgado, 2016; Delgado et al., 2011; McLellan et al., 2016; Osmond et al., 2012; Tomer et al., 2008; Schilling et al., 2012; and UMRSHNC, 2008) one may anticipate that further trends in increased crop yields will occur, soil fertility will be improved and sustained, and water quality improvements will result throughout the MRB. The evidence presented in this paper indicates that we have not yet arrived at our destination on this journey toward improved N stewardship and sustainability; and that many challenges also exist to improve the agronomic and environmental management of P. Yet, there is reason to stay the nutrient stewardship course, and to better partner with collective agronomic and environmental interests and programs, since all MRB and Gulf of Mexico nutrient and water quality stakeholders desire cleaner water and prosperity; for ourselves and our descendants.

We must each acknowledge that improvements in the Mississippi River Basin water quality, and a significantly smaller hypoxia zone in the Gulf of Mexico, will take time; perhaps longer than many had envisioned prior to 2008, and also in 2013. The science and data shared within this paper may help to identify where energy, time, resources and partnering opportunities may be better focused; to attain the MRB and Gulf of Mexico improved water quality goals that are collectively sought.

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Dr. Snyder is IPNI Nitrogen Program Director, located at Conway, Arkansas; E-mail: csnyder@ipni.net

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