Reducing the Dead Zone in the Gulf of Mexico:
Assessing the Costs to Agriculture

Background

Each summer a large hypoxic zone forms in the Gulf of Mexico, where dissolved oxygen is too low for many aquatic species to survive. This hypoxic zone is fueled by nutrient (nitrogen and phosphorus) runoff from the Mississippi/Atchafalaya River Basin (MARB). Excessive nutrient loads trigger excessive algae growth that rapidly consumes oxygen during decomposition. This decomposition in bottom waters, coupled with water column stratification that prevents mixing with oxygen-rich water at the surface, results in hypoxic conditions. Much of the nitrogen and phosphorus loads originate from sources relatively far upstream from the Gulf. Sources of nitrogen include agriculture—predominantly row crop agriculture and animal feeding operations—atmospheric deposition, urban runoff, and industrial and municipal discharges. Sources of phosphorus include agriculture, urban runoff, point sources, stream channels, and natural soil deposits.

Nutrient enrichment impacts living organisms in a number of ways (Rabalais and Turner, 2001; Diaz and Rosenberg, 2008; Rabalais et al., 2010). Mobile organisms (e.g. fish, shrimp) can often move out of hypoxic zones when oxygen levels start to fall. Bottom-dwelling mobile organisms such as eels are forced towards the surface where oxygen levels are higher, exposing them to greater predation. Benthic or bottom-dwelling organisms show visible signs of stress and eventually die as oxygen levels drop (Baustian, Craig, and Rabalais 2009; Baustian and Rabalais, 2009). In general, benthic communities in seasonally hypoxic waters are less diverse and contain less biomass than a healthy system, providing less food resources for bottom-feeding fishes and crustaceans (Baustian, Craig, and Rabalais 2009). Mobile animals, such as fish and shrimp, generally survive hypoxic events but often by moving into less optimal habitats (Craig 2012; Craig and Bosman 2012). Hypoxia is estimated to reduce habitat for brown shrimp by about 25 percent along the Louisiana coast (Craig et al, 2005). However, the impacts on fisheries have not been quantified (Rabalais and Turner, 2001).

The nutrient enrichment that causes hypoxia is also associated with Harmful Algal Blooms (HABs) (NSTC, 2016). The algal blooms may consist of species (dinoflagellates) that release toxins that adversely affect a wide variety of fish, shellfish, birds, and marine mammals. They can also cause illness and even death to humans. HABs can occur in both salt and fresh water systems.

In 2015 the Gulf hypoxic zone covered 16,760 square kilometers, which is above the five-year average (U.S. EPA, 2015), making it one of the largest in the world. The goal established by the Mississippi River Gulf of Mexico Watershed Nutrient Task Force is to limit the average size of the hypoxic zone to 5,000 square kilometers (U.S. EPA, 2015). Nitrogen and phosphorus loading reductions of up to 45 percent or more may be needed to achieve this goal (U.S. EPA SAB, 2008).

Nutrients are also a concern within the sub-basins of the MARB. High levels of nitrates in drinking water pose health risks, and treating water to meet EPA standards is costly. Recently, the Des Moines Iowa water works sued three upstream Iowa counties for excess nitrate levels originating from tile-drained cropland. In the Arkansas River Basin (which feeds into the Mississippi), the Tulsa Metropolitan Water Authority filed a lawsuit against the city of Decatur, Arkansas and six poultry companies in 2001, accusing them of polluting Tulsa’s drinking water supply. The end result was a court-ordered limit on the amount of poultry manure that could be spread on land in the watershed.

Excess phosphorus is the source of eutrophication of many lakes in the watershed, including some important recreational areas such as Ohio's Grand Lake Saint Marys. Businesses related to recreation on that lake lost an estimated $35 to $45 million in 2010 due to nutrient-related algal blooms (Davenport and Drake, 2011).

Agriculture and hypoxia

The MARB drainage area consists of 5 major river basins: Upper Mississippi, Lower Mississippi, Missouri, Ohio-Tennessee, and Arkansas-White-Red (table 1). USGS estimates that 60% of nitrogen and 49% of phosphorus entering the Gulf are from agricultural sources (cropland, fertilizers, manure, and nitrogen fixation) (Robertson and Saad, 2013). Corn/soybeans alone are estimated to be the source of 51.5% (45.6%) of nitrogen from the Mississippi (Atchafalaya) Basin. The Upper Mississippi and Ohio-Tennessee basins appear to be the watersheds that contribute the most nutrients on both a total basis and a load per acre basis (Robertson and Saad, 2013). These are regions characterized by intense row crop production (primarily corn and soybeans), as well as a relatively high percentage of cropland that is tiled to facilitate drainage.

Reducing nutrient losses from cropland has been a major conservation goal for USDA, EPA, and many MARB states. However, both nitrogen and phosphorus loadings to streams remain high and evidence suggests that loading to the Gulf have increased in recent years (Murphy et al., 2013). Flow-normalized nitrate concentrations at the mouth of the Mississippi rose 12 percent from 2000 to 2010 (EPA, 2015). Concentrations increased 29 percent in the Upper Mississippi basin and 43 percent in the Missouri basin.

Research has found that certain cropland—defined in terms of resource characteristics, farming practices, and geographic location—tend to contribute a disproportionate share of pollutants to the environment (Nowak, Bowen, and Cabot, 2006). The 10% of cropland with the highest nitrogen yields contribute 33% of the entire N load from cultivated cropland to the Gulf (White et al., 2014). This implies that abatement costs can be lowered through targeting, not simply to regions, but to particular fields within regions.

Goals for Gulf Hypoxia mitigation and the plan for achieving those goals are established by the Mississippi River Gulf of Mexico Watershed Nutrient Task Force, a partnership of the Federal Government and basin states. In 2001 the action plan for reducing, mitigating, and controlling hypoxia in the Northern Gulf of Mexico called for reducing the five-year running average areal extent of the hypoxic zone to less than 5,000 square kilometers by 2015. This would be achieved by implementing “specific, practical, and cost-effective voluntary actions”, and addressing all categories of sources of nitrogen and phosphorus (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2008). In 2015 the target date for achieving the goal was extended to 2035 in recognition of the magnitude of the task. An interim milestone of a 20% reduction in nitrogen and phosphorus loadings by 2025 was also set.

Several studies have examined the feasibility and costs of nutrient abatement in the Mississippi Basin and demonstrate the disproportionality of cropland contribution. McLellan et al. (2015) used the SPARROW model to conclude that a 45% nitrogen reduction goal in the Upper Mississippi-Ohio River Basins cannot be achieved by nitrogen fertilizer management alone, assuming that only a fraction of farmers would voluntarily take action. A combination of nitrogen management and nitrogen removal practices (cover crops, wetlands, buffers, and stream channel restoration) would also be required. Using the amount of cropland treated as a proxy for cost, they concluded that the goal could be reached with the least change to cropland by strategically placing nitrogen management on 25% of cropland and converting 2.5% of cropland to wetlands and forest buffers.

Rabotyagov et al. (2014) used CEAP data and an integrated assessment model linking the water quality effects of a set of conservation investment decisions across more than 550 sub-watersheds (HUC-8) to identify the least cost allocation of nutrient abatement across the entire MARB watershed. Process models were used to simulate the dynamics of conservation investment on nutrient delivery to the Gulf. This study demonstrated the efficiency gains of targeting both the set of sub-watersheds for investment in conservation as well as the level of investment within each sub-watershed. They found that the Action Plan goal could be achieved at an annual cost of $2.7 billion by targeting cropland conservation investments to the most cost-effective locations. However, this analysis did not account for market interactions, or include some important nutrient management practices such as cover crops and vegetative buffers.

Doering et al., (1999) used an agricultural sector model coupled with a runoff model to find the least cost option for reducing nutrient loss from cropland in the MARB by 20%. This analysis accounted for market interactions due to reduced fertilizer use and the restoration of wetland filters, as well as within-basin water quality benefits. The net social cost (producer and consumer surplus) was estimated to be $1.02 billion (2015 dollars). Using a similar analytic approach, Ribaudo et al. compared the cost-effectiveness of a fertilizer application standard and wetland restorations to achieve a range of edge-of-field nitrogen reduction goals (2001). They found that fertilizer reductions were more cost effective than wetland restorations up to a point. Wetland restoration became cost effective when large reductions in nitrogen were required.

Our analysis makes use of the ERS Regional Environmental Agricultural Programming (REAP) model and the NRCS Conservation Effects Assessment Project (CEAP) data to evaluate the economic consequences of alternative nitrogen and phosphorus reduction goals for meeting the nutrient reduction goals established in the Hypoxia Action Plan. In this initial phase of the study, abatement measures focus on adoption of in-field Best Management Practices in combination with extensive margin changes in cropland (land retirement) in response to mandatory targets for N and P loadings. One scenario addresses the most efficient way of meeting 20 and 40 percent nitrogen and phosphorus load reduction goals from agriculture to the Gulf without any constraints on where in the basin reductions are generated. The second is the most efficient way of meeting the nitrogen and phosphorus load reduction goals to the Gulf by reducing each sub-basin's contribution to the Gulf by 20 and 40 percent, which may be seen as more equitable. We assess the costs to the agricultural sector as well as environmental impacts both inside and outside the MARB.

A unique aspect of our analysis is that we assess the costs to the agricultural sector as well as environmental impacts both inside and outside the MARB. That is, the large reductions in nutrient loadings considered here directly affect commodity prices, hence agricultural production in other areas of the country.

Model and data

REAP is a mathematical optimization model that quantifies agricultural production and its associated environmental impacts for 267 production regions across the United States. REAP allocates production acreage among a discrete set of crop rotations available to each region and allocates the resulting agricultural products among a set of markets--including feed use, various processing sectors, other domestic use, and exports-- in order to maximize the economic surplus resulting from that production. REAP includes 10 major commodity crops (corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage), a number of livestock enterprises (dairy, swine, poultry, and beef cattle), and a variety of different processing technologies used to produce retail products from agricultural raw materials.

Crop production for a given region and soil type is simulated using the biophysical simulation model EPIC (Environmental Policy Integrated Climate model). EPIC is a field-scale crop response model that uses a daily time step to simulate crop growth and yields as well as soil impacts, hydrology, nutrient cycling, and pesticide fate under different tillage, crop rotation, soil, and weather scenarios. For the simulation of crop production, our regional analysis divides crop production in the United States into 267 regions, as defined by an overlay of the Assessment Subregion (defined by HUC4 hydrological boundaries), land resource regions, and farm production regions.

Each REAP model region includes a set of available crop rotations that are implemented using one of up to three tillage practices, under dryland or irrigated production (or both). The combination of rotation, tillage practice, and irrigation practice is referred to as a production enterprise and represents the basic unit of crop production economic activity in the REAP model. The selection of available production enterprises for each region was derived from the 2007 National Resources Inventory (NRI) data. When REAP solves for agricultural production patterns under changing climate, technology, or policy conditions, acreage in each region is distributed among available production enterprises based on an assessment of relative rates of return arising from differences in yields, costs, and returns. Acreage allocations are further constrained by a nested set of CET constraints representing acreage distribution constraints that are parameterized to capture historically observed patterns of production.

To explore adoption and impacts of best management practices within the MARB under various policy scenarios, we created alternative production enterprises within REAP to represent existing production enterprises that are modified to include best management practices such as drainage water management, cover cropping, structural erosion control, and nutrient management. To appropriately modify the yields, costs, and environmental impacts of enterprises that include BMPs, we used cost and impact estimates generated by the Conservation Effects Assessment Project for crop production within the MARB. The Conservation Effects Assessment Project (CEAP) was initiated in 2002 by USDA's Natural Resources Conservation Service (NRCS), Agricultural Research Service (ARS), and the National Institute of Food and Agriculture (NIFA) to evaluate the benefits from resource conservation on agricultural lands. A series of large watershed-scale studies was conducted as part of CEAP to assess the water quality benefits from conservation systems, including the entire MARB (Upper Mississippi, Lower Mississippi, Ohio-Tennessee, Missouri, and Arkansas-White-Red).

A field-level survey of farmers was conducted to obtained information on the extent of conservation practice use in the watershed over 2003-2006. The National Resources Inventory (NRI)—a statistical survey of conditions and trends in U.S. soil, water, and related resources on private lands conducted by NRCS since the 1970s—provided the statistical framework. Our data consisted of 12,759 sample points from the CEAP-NRI survey that collected detailed production and management data for agricultural fields over crop years 2001-2006. This includes cropland in production, cropland that is out of production through enrollment in the CRP or as part of a crop rotation, and pasture. The statistical properties of the observations capture the distribution of practices on all agricultural lands within the MARB.

The CEAP data also contain model estimates of erosion and nutrient emissions from fields under both the baseline and alternative management systems. Alternative management systems include nutrient management, structural erosion controls, cover crops, and drainage water management. In addition, cropland can be converted to permanent conservation cover (such as the CRP). More than one system can be employed on the same field, as in the case of nutrient management and erosion controls. Field-level effects of conservation practices were assessed using the Agricultural Policy Environmental Extender (APEX) (Williams et al., 2008; Gassman et al., 2009). APEX is a field-scale physical process model that simulates day-to-day farming activities, wind and water erosion, loss or gain of soil organic carbon, and edge-of-field losses of soil, nutrients, and pesticides. APEX also estimates crop yields for a given set management choices. Deliveries of pollutants from the edge of field to sub-watershed outlets and then to the Gulf were estimated with delivery coefficients from ARS that account for pollutant fate and transport losses.

Weather is a predominant factor in determining the emissions of nutrients and sediment from cropland. To capture the effects of weather, each scenario was simulated using 47 years (1960-2006) of daily weather data. The estimates used in our analysis are the means of these simulations and are treated as long-term averages.

Conversion of the CEAP results to impact factors that could be used to modify REAP's baseline practices involved several steps. CEAP points were first mapped to REAP rotations by excluding those points with non-REAP crops and assigning each remaining CEAP point a rotation based on its reported cropping history. Similarly, each CEAP point (now rotation) was assigned a tillage type based on an average of CEAP's historical residue estimates for each point, and each was assigned as either irrigated or dryland based on applied irrigation levels provided.

Once CEAP points were fully mapped to REAP production enterprises (rotation, tillage, and irrigation), the impact factors associated with the best management practices applied to each point were calculated. For most measures of yield and environmental impact we calculated the proportional change in impact as a result of imposing each BMP based on CEAP, applied to yield and environmental outcomes by production activities in the base REAP dataset. The costs of applying each of the best management practices were also generated by CEAP for each of the CEAP points. As a final step in mapping CEAP impacts to REAP-compatible impact estimates, a weighted average set of yields, costs, and environmental impact measures for each production enterprise was calculated at the REAP region level using the expansion factor provided for each CEAP point.

Not all baseline production enterprises in REAP could be mapped to a corresponding set of CEAP results. For those production enterprises with corresponding CEAP impacts, alternative production enterprises were created from the original REAP baseline enterprise by modifying the baseline yields, costs and environmental impacts using the weighted impacts calculated from the CEAP points. Once introduced into REAP, these alternative production enterprises become available during REAP's optimization and land can be allocated to the alternative production methods (with BMPs imposed) in order to meet nutrient reduction goals. The relative benefits in terms of nutrient reductions depend both on the best management practice imposed and on the REAP region's location relative to the Gulf; the delivery coefficients described above translate each region's activity into impacts on Gulf nutrient loading.

Results

Meeting the nitrogen (N) and phosphorus (P) loading constraints at the Gulf outlet most efficiently requires significant increases in the use of conservation measures, particularly drainage water management, erosion controls-nutrient management, and structural erosion controls, as well as an increase in land in the CRP (table 2). While the increase in nutrient management was not as dramatic, it was implemented on more cropland than any other management system. Crop acreage in conventional tillage and no-till decrease, while acreage in reduced-till increases.

Changes in production are sufficient to affect crop prices (table 3), which has an additional influence on production decisions within the MARB, as well as affecting production outside the MARB. The prices of corn, cotton, sorghum, oats, rice and hay are all estimated to increase under both the 20% and 40% constraints at N and P loads to the Gulf outlet. Prices of soybeans, wheat, and barley are estimated to decline. Changes in feed grain prices affect the livestock sector. Prices of fed beef, pork, and broilers are estimated to increase slightly from meeting the outlet-level nutrient constraints.

Under the 40% Gulf outlet constraint, crop acreage in the MARB is estimated to decline by 1.6%, with corn acreage declining 2.3% and hay declining 5.7% (table 4). Cropland outside the basin increases 3.7%, resulting in a net national decline in cropland acreage of 0.1%. Edge-of-field nutrient and sediment losses decrease significantly in the MARB, but increase in most watersheds outside the MARB (table 5), driven by expansion of fieldcrop production due to higher crop prices. In the Mid-Atlantic, where the Chesapeake Bay is located, and in the Great Lakes region, increases in nutrient and sediment loads could be a concern to states trying to address important water quality problems.

Within the MARB, the largest percentage reductions in nutrient and sediment loads occur in the Ohio, Lower Mississippi, and Arkansas-White-Red basins. The Missouri Basin actually sees an increase in nitrogen. This region delivers relatively little pollutant load to the Gulf, given the distances involved, climate, and the types of crops grown. Therefore, the scenario that imposes a constraint on nutrient loadings to the Gulf has a much more limited impact on production practices in this region relative to other sub-basins in the MARB. The increase in crop prices leads to some intensification in nitrogen use, resulting in small increases in average field-level losses of nitrogen and erosion. The greatest N load reductions to the Gulf come from the Ohio, Upper Mississippi, and Lower Mississippi basins (table 6). The greatest P load reductions to the Gulf come from the Ohio and Lower Mississippi basins.

Overall, the economic impact to agriculture sector within the MARB is estimated to be a gain of $24 million for the 20% constraint and a loss of $139.2 million for the 40% constraint (table 7). These changes reflect the increase in production costs from adopting conservation on a portion of cropland, foregone production on reduced cropland acreage, and the changes in crop prices that result from shifting patterns of production. The price increases result in an increase in producer net returns outside the region of $219.4 million and $677.4 million.

When each sub-basin within the MARB is constrained to reduce their contribution to Gulf N and P loads by 20% and 40%, the production impacts and costs are greater. Regions that contribute relatively little to the Gulf, such as the Missouri Basin, are forced to adopt conservation measures which are more costly on a per-unit-pollutant-delivered basis than cropland in other regions. Similarly, regions that can provide additional abatement more cheaply are not required to do so. More acres of cropland need to be treated with conservation measures, adjustment costs are greater, and crop prices rise more sharply. With higher crop prices, nutrient and sediment losses outside the MARB increase more than under the outlet level constraint (table 8).

The sub-basin level constraints removed substantially more crop acreage from production (increase in CRP acres) than under the Outlet constraint. A significant reallocation of crop acreage occurs within the MARB, with greater reductions in the Upper Mississippi, Missouri, and Tennessee basins in particular. Acreages declined across all major crops (corn, hay, soybeans, wheat) within the MARB under the sub-basin level constraint.

Edge-of-field pollutant losses are greatly reduced within the MARB, but the increase in crop prices results in higher losses of pollutants in most regions outside the MARB than for the optimal scenario (table 8). Crop producers in the MARB see a reduction in net returns of $63.6 million for the 20% constraint, and $1.6 billion for the 40% constraint. Outside the MARB, crop producers see increases in net returns of $803.3 million and $1.8 billion.

Conclusions

Our results suggest that the proposed nutrient reduction goals for reducing the size of the hypoxic zone in the Gulf of Mexico will have sizable impacts on the agricultural sector in the MARB. Because of this region's position in the national agricultural economy, the results indicate that crop prices will be affected by the changes in production practices within the MARB to meet nutrient reduction goals and influence production outside the region. The higher crop prices could be a windfall of sorts for producers outside the basin. However, the intensification of production has some undesirable environmental side-effects, such as increased environmental loadings of nitrogen, phosphorus, and sediment.

The study also finds that the most efficient allocation of conservation measures for meeting the eventual Gulf goal would cost crop producers in the MARB about $139 million per year. This is much less than estimates recently reported in the literature, but those studies did not consider changes in crop prices. Crop price increases cushion the sector costs incurred for implementing conservation measures and other adjustments to production. In addition, our study provided more options for addressing nutrient pollution which could also reduce costs.

When all sub-basins are required to meet the N and P reduction goals for the Gulf, the research also finds that costs are much higher. This additional cost could be considered a cost of a more “equitable” allocation of abatement. However, each region is dealing with its own internal water quality issues, and the more equitable allocation would likely provide more in-basin water quality benefits.

Table 1 – Farms, agricultural acres, and animal units in the MARB, by sub-basin

	Farms	Cropland (million acres)	Pasture/range (million acres)	Animal units (millions)
Upper Mississippi	278,687	63.5	13.7	11.6
Ohio-Tennessee	344,536	26.8	23.3	8.7
Missouri	267,832	95.1	180.6	23.0
Arkansas-White-Red	216,085	35.3	77.6	16.1
Lower Mississippi	76,362	20.3	8.0	1.8
Total	915,670	241.0	303.2	64.2

From 2007 Census of Agriculture

Table 2 - Change in acreage of cropland in conservation systems in the MARB for a 40% reduction in N and P loads to the Gulf

	Base acreage	Outlet-level constraint	Sub-basin level constraint
Conservation system	million acres	percent	
NM	9.1	51.6	173.1
FT	0.3	686.2	2737.4
ENM	0.5	456.2	1436.8
CC	1.0	158.4	1040.8
DWM	2.5	109.6	265.6
CRP	13.8	24.4	45.6
Tillage system			
Conventional till	87.2	-5.1	-13.5
Reduced till	50.0	8.1	11.8
No till	93.9	-14.3	-23.3

NM = nutrient management; FT = structural erosion controls; ENM = NM+FT; CC = cover crops; DWM = drainage water management; CRP = conservation reserve program

Table 3 - Percentage change in crop prices from meeting MARB nitrogen and phosphorus constraints at the Gulf outlet and at the sub-basins outlets

	Outlet-level constraint		Sub-basin level constraint	
Crop	20%	40%	20%	40%
	percent			
Corn	1.2	3.1	4.3	7.2
Soybeans	-0.3	-0.2	0.1	0.9
Wheat	-0.6	-0.4	0.1	3.4
Cotton	0.8	2.2	-0.2	-0.4
Sorghum	0.9	1.8	4.1	7.0
Barley	-1.0	-2.5	-0.2	-0.1
Oats	1.1	2.9	10.9	18.5
Rice	2.0	6.5	7.0	15.4
Hay	0.3	0.9	0.8	1.9
Fed beef	0.2	0.4	0.6	1.1
Pork	0.1	0.2	0.5	1.3
Broilers	0.3	0.8	1.1	2.0

Table 4 - Change in acreage of major crops for meeting a 40% MARB nitrogen and phosphorus constraints at the Gulf outlet and at the sub-basins outlets

Crop	**Base**	**Outlet-level constraint**	**Sub-basin level constraint**
	Million acres	**% change**	
Corn	**95.08**	**-1.3**	**-1.9**
Outside MARB	16.24	3.6	6.5
Inside MARB	78.84	-2.3	-0.4
Hay	**62.27**	**-2.6**	**-4.8**
Outside MARB	23.78	2.6	4.9
Inside MARB	38.49	-5.7	-10.9
Soybeans	**63.37**	**0.7**	**-1.6**
Outside MARB	10.56	1.6	2.6
Inside MARB	52.81	0.6	-2.5
Wheat	**61.45**	**2.9**	**1.3**
Outside MARB	18.35	3.2	8.5
Inside MARB	43.10	2.8	-1.7
Total acres	**333.02**	**-0.1**	**-2.1**
Outside MARB	91.30	3.7	6.5
Inside MARB	241.72	-1.6	-5.4

Table 5 - Percent change in edge-of-field loadings by HUC2 from meeting constraints on nitrogen and phosphorus at the Gulf outlet

	20% Loading Reduction			40% Loading Reduction		
Watershed (HUC)	N	P	Erosion	N	P	Erosion
Mississippi Basin						
Ohio (05)	-20.7	-14.5	-8.4	-45.5	-39.2	-21.9
Tennessee (06)	-5.6	-9.8	-8.8	-20.4	-26.5	-21.9
Upper Mississippi (07)	-12.1	-4.4	-1.6	-24.3	-12.4	-8.8
Lower Mississippi (08)	-23.3	-23.1	-20.1	-50.3	-50.5	-50.5
Missouri (10)	0.1	-7.1	2.1	2.2	-19.0	4.8
Arkansas-White-Red (11)	-24.3	-57.6	-7.1	-30.9	-61.8	-0.4
Sub-total	**-13.8**	**-19.9**	**-3.0**	**-26.1**	**-32.6**	**-6.5**
Outside Basin						
New England (01)	0	0.4	0.4	0.1	0.1	0.3
Mid-Atlantic (02)	0.2	0.4	0.4	0.4	0.8	0.8
South Atlantic-Gulf (03)	1.4	1.4	1.6	3.5	3.4	3.6
Great Lakes (04)	0.6	0.3	1.0	1.2	0.5	1.8
Souris-Red-Rainy (09)	1.2	1.2	2.3	3.0	3.2	6.0
Texas-Gulf (12)	3.8	4.2	5.7	9.5	10.5	14.2
Rio Grande (13)	1.3	1.9	2.7	3.7	4.7	6.9
Upper Colorado (14)	1.7	0.4	2.2	4.6	0.9	6.3
Lower Colorado (15)	1.2	4.3	0.2	1.7	7.0	0.4
Great Basin (16)	6.2	-0.7	2.5	20.8	-0.9	1.4
Pacific Northwest (17)	0.9	-0.3	2.5	2.6	-0.9	7.2
California (18)	1.4	-0.6	0.4	4.0	-2.5	0.7
Sub-total	**1.2**	**0.3**	**3.1**	**3.0**	**0.1**	**7.8**
US total	**-7.8**	**-11.0**	**-1.0**	**-14.4**	**-18.2**	**-1.9**

Table 6 - Shares of load reduction in the MARB from 40% constraints on N and P at the outlet to the Gulf

	Outlet-level constraint	
Sub-basin	Share of N load reduction	Share of P load reduction
	Percent	
Ohio	40.4	33.7
Tennessee	1.3	1.2
Upper Mississippi	24.9	6.8
Lower Mississippi	24.7	34.6
Missouri	0	4.7
Arkansas-White-Red	8.8	19.0

Table 7 - Changes in producer net returns from meeting MARB nitrogen and phosphorus constraints

	Outlet-level constraint		Sub-basin level constraint	
Region	20%	40%	20%	40%
MARB	24.3	-139.2	-63.6	-1584.4
Outside MARB	219.4	677.4	803.3	1766.6
Total	243.7	538.2	739.7	182.1

Table 8 - Percent change in edge-of-field loadings by HUC2 from meeting sub-basin level constraints on nitrogen and phosphorus

	20% Loading Reduction			40% Loading Reduction		
Watershed (HUC)	N	P	Erosion	N	P	Erosion
Mississippi Basin						
Ohio (05)	-19.9	-20.0	-8.3	-40.0	-40.0	-20.3
Tennessee (06)	-20.0	-20.0	-20.4	-40.0	-39.9	-31.1
Upper Mississippi (07)	-20.6	-20.1	-14.8	-40.7	-40.6	-32.7
Lower Mississippi (08)	-20.0	-20.9	-17.5	-40.0	-42.0	-47.0
Missouri (10)	-18.5	-18.6	-5.1	-37.5	-40.1	-26.8
Arkansas-White-Red (11)	-18.5	-18.6	-5.0	-37.5	-37.5	-18.3
Sub-total	**-19.8**	**-20.0**	**-9.8**	**-39.9**	**-26.6**	**-28.0**
Outside Basin						
New England (01)	0	0.1	0.4	0	0.1	0.4
Mid-Atlantic (02)	0.4	0.1	1.0	0.6	1.5	1.5
South Atlantic-Gulf (03)	2.6	2.9	3.0	4.0	3.9	4.0
Great Lakes (04)	1.3	0.5	1.7	1.5	0.5	1.6
Souris-Red-Rainy (09)	4.0	4.2	7.6	6.4	6.7	11.2
Texas-Gulf (12)	10.2	10.7	14.8	14.3	15.3	21.1
Rio Grande (13)	4.8	6.1	8.9	6.3	7.4	10.9
Upper Colorado (14)	5.2	0.9	7.9	7.0	1.2	12.2
Lower Colorado (15)	7.2	25.5	0	3.3	13.3	-0.4
Great Basin (16)	27.5	2.6	10.0	34.2	-4.2	13.8
Pacific Northwest (17)	3.3	-1.1	9.4	6.0	-2.1	14.1
California (18)	2.8	-3.5	0.8	7.7	-7.6	0.2
Sub-total	**2.8**	**-0.2**	**8.6**	**4.9**	**-2.0**	**12.4**
US total	**-10.6**	**-10.9**	**-3.8**	**-21.6**	**-24.4**	**-15.0**

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