United States Department of Agriculture

Economic
Research
Service

Economic
Research
Report
Number 258

September 2018

Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution

Elizabeth Marshall, Marcel Aillery, Marc Ribaudo, Nigel Key, Stacy Sneeringer, LeRoy Hansen, Scott Malcolm, and Anne Riddle

United States Department of Agriculture

Economic Research Service
www.ers.usda.gov

Recommended citation format for this publication:

Marshall, Elizabeth, Marcel Aillery, Marc Ribaudo, Nigel Key, Stacy Sneeringer, LeRoy Hansen, Scott Malcolm, and Anne Riddle. *Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution,* ERR-258, U.S. Department of Agriculture, Economic Research Service, September 2018.

Cover is a derivative of images from Getty Images.

Use of commercial and trade names does not imply approval or constitute endorsement by USDA.

To ensure the quality of its research reports and satisfy governmentwide standards, ERS requires that all research reports with substantively new material be reviewed by qualified technical research peers. This technical peer review process, coordinated by ERS' Peer Review Coordinating Council, allows experts who possess the technical background, perspective, and expertise to provide an objective and meaningful assessment of the output's substantive content and clarity of communication during the publication's review.

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at How to File a Program Discrimination Complaint and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

United States Department of Agriculture

Economic Research Service

Economic
Research
Report
Number 258

September 2018

Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution

Elizabeth Marshall, Marcel Aillery, Marc Ribaudo, Nigel Key, Stacy Sneeringer, LeRoy Hansen, Scott Malcolm, and Anne Riddle

Abstract

Every summer, a large area forms in the northern Gulf of Mexico where dissolved oxygen becomes 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), most of which comes from agriculture. This analysis used the ERS Regional Environment and Agriculture Programming (REAP) model and data from the USDA Conservation Effects Assessment Project (CEAP) to assess the most cost-effective way of achieving a 45-percent reduction in cropland nutrient loads to the Gulf. Strategies involve adoption of management practices that reduce nutrient loss from fields to water resources, off-field practices for intercepting nutrients, retirement of marginal cropland, and other changes in crop management. Results suggest that proximity to the Gulf was a major factor in the location of nutrient-reduction efforts when reducing Gulf hypoxia was the only goal. When local as well as Gulf nutrient-reduction targets are applied, nutrient-reduction efforts are spread more evenly across the MARB. Adopting nutrient management practices, restoring wetlands, and retiring cropland to meet water quality goals also increased commodity prices, resulting in more intensive production outside the MARB and increased nutrient and sediment loadings to water in other watersheds.

Keywords: hypoxia, targeting, compliance, Gulf of Mexico, Mississippi/Atchafalaya River Basin, conservation practices, wetlands, buffers, nitrogen reduction, phosphorus reduction, nutrient runoff, dead zone.

Acknowledgments

The authors would like to thank Jay Atwood (USDA, Natural Resources Conservation Service-Blackland Research and Extension Center (BREC)) for his invaluable support in helping us incorporate the CEAP data into the REAP modeling framework. In addition, we would like to thank Robin Taylor (BREC) and Todd Campbell (Iowa State University) for technical support with the biophysical modeling, and Ryan Williams (ERS) for GIS (Geographic Information System) support in incorporating spatial data into REAP. The authors also thank the following for technical peer reviews: Keith Fuglie, USDA Economic Research Service; Mark Peters, USDA Natural Resources Conservation Service; Sergey Rabotyagov, University of Washington; Mindy Selman, USDA Office of the Chief Economist; and James Shortle, Pennsylvania State University. We also thank Dale Simms and Curtia Taylor, USDA/ERS, for editorial and design services.

Contents

Contents

United States Department of Agriculture

A report summary from the Economic Research Service *September 2018*

United States Department of Agriculture

Economic Research Service

Economic Research Report Number 258

September 2018

Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution

Elizabeth Marshall, Marcel Aillery, Marc Ribaudo, Nigel Key, Stacy Sneeringer, LeRoy Hansen, Scott Malcolm, and Anne Riddle

Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution

Elizabeth Marshall, Marcel Aillery, Marc Ribaudo, Nigel Key, Stacy Sneeringer, LeRoy Hansen, Scott Malcolm, and Anne Riddle

What Is the Issue?

Every summer, a large area forms in the northern Gulf of Mexico where dissolved oxygen becomes too low for many aquatic species to survive. This "hypoxic zone" is fueled by nutrient (nitrogen and phosphorus) losses from the Mississippi/Atchafalaya River Basin (MARB), a region containing about 70 percent of U.S. cropland. Research has established that nitrogen (N) and phosphorus (P) loadings into the Gulf originate largely from cropland, with agriculture contributing about 60 percent of N and nearly half of P. The Mississippi River Gulf of Mexico Watershed Nutrient Task Force, comprised of State and Federal agencies and led by the U.S. Environmental Protection Agency (EPA), established a goal to reduce the average size of the summer hypoxic zone from 5,236 square miles (current 30-year average) to 1,931. Achieving this goal could require a reduction in nutrient loads to the Gulf by 45 percent or more, which could have significant economic impacts on producers and consumers.

What Did the Study Find?

We modeled changes that would achieve a 45-percent reduction in N and P loads from cropland to the Gulf at least cost to producers and consumers. The analysis considers two policy implementation scenarios. One focused only on reducing overall nutrient loads to the Gulf, regardless of where those nutrients originated ("Gulf Constraints"). Another met this same goal by requiring a 45-percent reduction in N and P loadings from each of 135 subregions (REAP model production regions) within the Mississippi/Atchafalaya watershed ("Regional Constraints"), thereby potentially addressing both Gulf and local water quality objectives.

- ***The most cost-effective method to meet the Gulf goal focuses nutrient-reduction efforts in the Lower Mississippi sub-basin.*** While the largest baseline contributors to nitrogen deliveries to the Gulf are the Ohio and Upper Mississippi Basins, with more than 60 percent of baseline nitrogen loadings, the Lower Mississippi accounts for more than 43 percent of N and P load reductions to the Gulf under a cost-effective strategy for hypoxia control. Costs per unit of nutrient reduction are lower here than in other regions, in part because of proximity to the Gulf and less opportunity for instream removals of N and P as nutrients flow to the Gulf.

- ***Addressing both Gulf and local water quality objectives would spread the conservation effort more evenly among sub-basins.*** The total cost of reducing nutrient discharge to the

ERS is a primary source of economic research and analysis from the U.S. Department of Agriculture, providing timely information on economic and policy issues related to agriculture, food, the environment, and rural America.

Gulf would be higher as more treatment occurs in areas with higher nutrient-reduction costs. However, local water quality benefits (beyond reducing Gulf hypoxia) would likely occur as total nutrient discharges decline across the basin.

- ***Providing incentives for the reduction of a single nutrient (N or P) results in some reduction of the other nutrient.*** The strength of the association varies regionally, and the effect is greater when N is the targeted nutrient.
- ***Implementing nutrient-reduction measures to meet Gulf hypoxia goals would reduce commodity production and increase commodity prices.*** MARB cropland in production would decline by 4.4 percent under the Gulf constraints and 10.9 percent under the regional constraints. As a result, the prices of most crops would rise, with some major crops growing up to 10 percent costlier under the Regional Constraints scenario. Higher prices would partially offset the costs to crop producers of reducing nutrient loads and pass some of the cost on to consumers of agricultural products, including livestock producers, food consumers, and biofuel feedstock users.
- ***Higher commodity prices lead to an intensification of production in regions outside the MARB.*** Without additional constraints on nutrient loadings to water bodies outside the MARB, non-MARB cropland in production expands by 2.1 to 4.0 percent. As a result, nutrient and sediment losses increase 1.2 to 5.0 percent across non-MARB regions.
- ***The least-cost strategy for nutrient reduction within the MARB involves a mix of on-field and off-field conservation practices.*** Optimally placed wetlands and buffers generally provided the most cost-effective nitrogen reductions to the Gulf. Drainage water management, nutrient management, and cover crops, when used with structural erosion controls, were also generally relatively cost effective.

Financial incentives to farmers would likely be required to achieve the range of conservation practices and the scale of nutrient reduction necessary to meet Gulf hypoxia goals, particularly where the benefits of the nutrient-reduction practices occur primarily off the farm. An analysis supplemental to the REAP analysis explores how a nutrient-compliance policy for USDA farm program benefits could incentivize farmers with excess nitrogen applications to implement improved nutrient management. Farms with the highest excess application rates tend to receive the most program payments per acre, suggesting that a nutrient-compliance policy could effectively reduce nutrient runoff. However, nutrient management is most likely to be adopted in sub-basins that contribute fewer nutrients to the Gulf, reducing the overall impact on Gulf water quality from this policy alone.

How Was the Study Conducted?

The study used the ERS Regional Environment and Agriculture Programming (REAP) model to identify the combination of conservation practices, crop rotations, tillage, irrigation, and land-use change that meets nutrient-reduction goals at least cost. Data from USDA's Conservation Effects Assessment Project (CEAP) were used to evaluate the environmental and economic impacts of applying conservation practices on agricultural lands. Nutrient-delivery coefficients developed by USDA's Agricultural Research Service (ARS) were used to estimate the share of edge-of-field nutrient losses from across the MARB that reaches the Gulf. ERS researchers used the REAP model to estimate the mix of conservation strategies and farm production changes across the MARB region that would reduce nitrogen and phosphorus loads from agriculture to the Gulf of Mexico by at least 45 percent at the lowest total cost to producers and consumers. Additional nutrient compliance scenarios draw on data from the 2012 Census of Agriculture and from USDA conservation, commodity, insurance, and disaster programs to estimate excess nutrient use (above crop needs) and program benefits at the farm level.

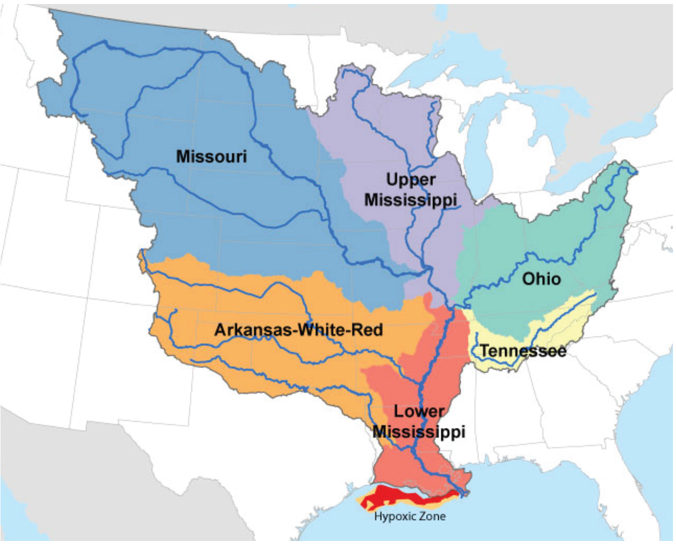
Reducing Nutrient Losses From Cropland in the Mississippi/Atchafalaya River Basin: Cost Efficiency and Regional Distribution

Chapter 1: Introduction

Each summer, a large area forms in the Gulf of Mexico where dissolved oxygen becomes 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), which consists of six major sub-basins: Upper Mississippi, Lower Mississippi, Missouri, Ohio, Tennessee, and Arkansas-White-Red (figure 1.1).[1] Large nutrient loads can trigger algal blooms that rapidly consume oxygen during decomposition (also known as eutrophication) (U.S. EPA, SAB, 2008). This decomposition in bottom waters, coupled with water column stratification that prevents mixing with oxygen-rich water at the surface, results in hypoxic conditions. The nitrogen and phosphorus loads in the MARB originate largely from sources far upstream from the Gulf. Sources of nitrogen include agriculture—predominantly commercial fertilizer and manure applied to cropland (see box, "Pathways for Nutrient Losses From Fields")—as well as atmospheric deposition, urban runoff, and industrial/municipal discharges. Sources of phosphorus include row crop agriculture and animal feeding operations, urban runoff, industrial/municipal discharges, stream channels (legacy loads), and natural soil deposits.

Figure 1.1

The hypoxic zone develops at the mouth of the Mississippi/Atchafalaya River Basin, which is subdivided into six sub-basins



Note: The area and location of the hypoxic zone are estimated based on data collected by the Louisiana State University and Louisiana University Marine Consortium during the National Oceanic and Atmospheric Administration (NOAA) 2017 Shelfwide Cruise.
Source: USDA, Economic Research Service.

---

[1] The Atchafalaya River is a distributary of the Mississippi River in south-central Louisiana. The Atchafalaya River receives approximately 30 percent of the water flow of the Lower Mississippi, with the remaining 70 percent continuing through the main Mississippi River channel to the southeast.

Pathways for Nutrient Losses From Fields

Runoff—Surface runoff of dissolved nitrogen and phosphorus occurs when fertilizer and/or manure are applied on the field surface and rain or irrigation water transports nutrients off the field before they enter the soil.

Ammonia volatilization—Significant amounts of nitrogen can be lost to the atmosphere as ammonia (NH_3) if animal manure or urea is surface-applied and not immediately incorporated into the soil (Hutchinson et al., 1982; Fox et al., 1996; Freney et al., 1981; Sharpe and Harper, 1995; Peoples et al., 1995). Additionally, warm weather can accelerate the conversion of manure and other susceptible inorganic nitrogen fertilizers to ammonia gas. Volatilization is not an issue with phosphorus.

Denitrification—When oxygen levels in the soil are low, some microorganisms known as denitrifiers will convert soil nitrate to nitrogen (N_2) and nitrous oxide (N_2O), both of which are gases lost to the atmosphere (Mosier and Klemedtsson, 1994). Nitrogen gas is not an environmental issue, but N_2O is a powerful greenhouse gas. Denitrification usually occurs when nitrate is present in the soil, soil moisture is high or there is standing water, and soils are warm.

Leaching—Leaching occurs when there is sufficient rain and/or irrigation to move dissolvable nitrogen and phosphorus compounds through the soil profile (primarily nitrate and orthophosphate) (Novotny and Olem, 1994). The nutrients may end up in underground aquifers or in surface water via tile drains and subsurface flow. Tile drains may be a chief passageway by which nitrogen moves from cropland soils to surface water (Turner and Rabalais, 2003; Randall et al., 2008; Randall et al., 2010).

Soil erosion—Nitrogen and phosphorus can be lost from the soil surface when attached to soil particles or as a component of soil or surface organic matter (including applied manure) that is carried off the field by wind or water. Erosion is of particular importance for the movement of phosphorus, which readily attaches to soil particles. Although wind and water erosion can be observed across all parts of the MARB, wind erosion is more prevalent in dry regions and water erosion in humid regions.

In 2017, the Gulf of Mexico's hypoxic zone covered 8,776 square miles, the largest size measured to date (Louisiana Universities Marine Consortium, 2017). Hypoxia affects living organisms in a number of ways (Rabalais and Turner, 2001; Diaz and Rosenberg, 2008; Rabalais et al., 2010). Mobile animals, such as fish and shrimp, generally survive hypoxic events, often by moving out of hypoxic zones when oxygen levels start to fall and into less-than-optimal habitats (Craig, 2012; Craig and Bosman, 2012; Smith et al., 2014). For example, hypoxia has reduced habitat for brown shrimp by an estimated 25 percent along the Louisiana coast (Craig et al., 2005), and a 2017 study of the Gulf of Mexico shrimp fishery found a link between hypoxia and higher prices for large-sized shrimp (Smith et al., 2017).

Bottom-dwelling organisms such as eels are forced toward the surface where oxygen levels are higher, exposing them to greater predation. Benthic or bottom-dwelling organisms that are less mobile, such as shellfish and worms, 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 in a healthy system, providing less food resources for bottom-feeding fishes and crustaceans (Baustian, Craig, and Rabalais 2009).

Nutrient runoff is also a water quality concern within sub-basins of the MARB. High levels of nitrates in drinking water pose health risks, and treating water to meet EPA drinking water standards can be costly. Phosphorus runoff can degrade the quality of freshwater lakes and streams by causing algal blooms. Thus, reducing nutrient loads to address hypoxia could also provide water treatment and recreation benefits within the MARB (U.S. EPA, 2017).

Agriculture is estimated to be the primary source of the nutrients entering the Gulf. Researchers from the U.S. Geological Survey (USGS) estimate that 60 percent of nitrogen and 49 percent of phosphorus entering the Gulf are from agricultural sources (cropland, fertilizers, manure, and nitrogen fixation) (Robertson and Saad, 2013). The Upper Mississippi and Ohio basins appear to be the watersheds that contribute the most nutrients, both total and per acre (Robertson and Saad, 2013). These regions are characterized by intensive row crop production (primarily corn and soybeans), as well as a high percentage of cropland that is tiled (underground, perforated piping that lowers the water table to enable cultivation) to facilitate drainage.

Tile drainage is of particular importance in the MARB (Petrolia and Gowda, 2006). Tiling fields to lower water tables increases productivity but also offers a direct and rapid conduit for nitrate-rich water from the field to surface-water bodies. Much of the highly productive cropland in Iowa, Illinois, and Ohio was originally wetland and can be farmed only with drainage. In the Upper Mississippi sub-basin, an estimated 52 percent of cropland is at least partly drained (USDA NASS, 2014). Research indicates that nutrient management practices vary in effectiveness on tile-drained lands; vegetative buffers, for instance, are not as effective at reducing nutrient losses on tiled cropland because, unless modified, the drains tend to bypass buffers and deliver nutrients directly to surface water (Dinnes et al., 2002).

Reducing nutrient losses from cropland has been a major conservation goal for USDA, EPA, and many MARB States. Conservation practices are already established on cropland throughout the MARB. Analysis conducted under the Conservation Effects Assessment Program (CEAP) suggests that conservation practices in place from 2003 to 2006 were likely to already have had substantial potential savings in field-level nutrient losses in the Missouri and Arkansas-White-Red sub-basins. Those regions had relatively few remaining acres designated as “critically undertreated”—1.1 million acres (1.2 percent of cultivated cropland) and 1.3 million acres (3.4 percent of cultivated cropland), respectively (USDA NRCS, 2012a; USDA NRCS, 2013a). In contrast, the Upper and Lower Mississippi sub-basins were found to have high potential for additional reductions in nutrient loss, with 9.0 million acres (14.3 percent of cultivated cropland) and 6.9 million acres (31 percent of cultivated cropland), respectively, designated as “critically undertreated” (USDA NRCS, 2012b; USDA NRCS, 2013b).

Overall, both nitrogen (N) and phosphorus (P) discharges to streams and loadings to the Gulf remain high (U.S. EPA, 2017). Because the cost and effectiveness of practices vary according to landscape characteristics and composition—and because practices typically involve multiple benefits (e.g., nutrient loss and soil health)—further reduction in nutrient loadings originating within the MARB is likely to entail a broad portfolio of mitigation strategies.

Gulf action plan

Mitigation goals for Gulf hypoxia and the plan for achieving those goals are established by the Mississippi River Gulf of Mexico Watershed Nutrient Task Force (also known as the Hypoxia 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 5-year running average areal extent of the hypoxic zone to less than 1,931 square miles by 2015. Such a reduction could require a cut in nutrient loads to the Gulf by 45 percent or more (U.S. EPA, 2008). This would be achieved by implementing "specific, practical, and cost-effective voluntary actions," and addressing all categories of nitrogen and phosphorus sources (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 task's magnitude, with an interim milestone—20-percent reduction in nitrogen and phosphorus loadings by 2025—also set (U.S. EPA, 2017).

The geographic scale of the MARB drainage basin suggests that coordination across political boundaries and sources will be required to achieve the Task Force hypoxia goals. This proved to be a source of contention in the Chesapeake Bay watershed, a much smaller geographic area (Ribaudo et al., 2014). On the agricultural side, there is a very large number of privately managed sources to consider. The origination, transport, and fate of nutrients from individual fields cannot be directly observed and require significant data and modeling in order to design effective mitigation strategies (Rabotyagov et al., 2014a, Shortle et al., 2012; Ribaudo et al., 1999).

A long line of research has found that certain cropland contributes a disproportionate share of pollutants to the environment, due to a combination of management and land characteristics (soils, slope, proximity to water) particularly conducive to nutrient loss (Nowak et al., 2006; Ribaudo et al., 2014). For example, a third of the entire cultivated N load to the Gulf has been attributed to 10 percent of cropland in the MARB (White et al., 2014). While the heterogeneity of soil types complicates identification and treatment of nutrient concerns, across farms or even within a single field, there may be potential for lowering the total costs of achieving water quality goals by targeting such croplands.

The costs of nutrient abatement are not limited to the implementation costs of practices. Changing crop rotations, nutrient management, and drainage management—as well as shifts in total cropland under production—could affect crop prices, spreading impacts to consumers of agricultural products and to regions outside the MARB (Doering et al., 1999). The challenge for policymakers is to identify areas of the MARB where nutrient loadings can be reduced most cost-effectively and to devise policies that induce cropland managers in those regions to reduce nutrient losses from fields.

In this report, we focus on two issues. One is identifying a cost-effective allocation of crop management and conservation measures across the MARB that achieves reductions in N and P loadings to the Gulf from cropland that are consistent with the goals adopted by the Gulf Hypoxia Task Force, where cost-effectiveness is defined as meeting the nutrient-reduction goal at the least cost to consumers and producers. The ERS Regional Environment and Agriculture Programming (REAP) modeling system and data from the USDA Conservation Effects Assessment Project (CEAP) enable us to alternatively evaluate nutrient-reduction goals for the Gulf only, and for the Gulf together with production regions within the MARB. Various measures are available to farmers to reduce nutrient losses from fields, including nutrient management, cover crops, drainage water management, erosion controls, vegetative buffers, wetland restoration, tillage, crop rotations, irrigation, and land retirement. The second issue we address is whether management changes made within the MARB to address Gulf hypoxia are of sufficient magnitude to influence commodity prices, and we assess implications for regional production and environmental impacts outside the MARB.

Chapter 2: Scenarios, Model, and Data

A cost-effective allocation of management actions to meet nutrient-reduction goals in the MARB requires that the physical and hydrologic features of a complex landscape be linked to the economic consequences of management choices at specific geographic locations. This presents challenges for a region as large and diverse as the MARB (containing about 70 percent of U.S. cropland) (Nowak et al., 2006; Batie, 2010). Thousands of individual water bodies—including rivers and streams, wetlands, lakes, estuaries, and groundwater aquifers—can be affected by agricultural production. The environmental effect of individual farms (even individual fields) on these resources vary widely, even in small regions, depending on the mix of crop and livestock commodities produced as well as site-specific geographic factors (e.g., topography, soils, hydrology, landscape position). Individual effects at the field level accumulate downstream and eventually impact the Gulf. Adding to the complexity, the relationships between agriculture and downstream water quality cannot be adequately represented by simple linear relationships (Batie, 2010).

Several studies have examined the changes in management that would be required to cost-effectively reduce nutrient loads, either for the entire basin or for some of the major sub-basins (usually the Upper Mississippi and Ohio). Some relevant findings include:

- Meeting the goal of the Gulf Action Plan (a 5,000-km^2 hypoxic zone) by targeting conservation measures to the most cost-effective locations throughout the entire MARB would involve a net cost to producers of $2.7 billion (Rabotyagov et al., 2014b). However, market effects were not accounted for in this study, and some important practices such as cover crops, drainage water management, and vegetative buffers were not considered.
- Fertilizer management alone cannot achieve water quality goals (McLellan et al., 2015).
- Optimally controlling for one nutrient (nitrogen or phosphorus) also to a variable extent controls the other (Rabotyagov et al., 2010).
- Nutrient loss from cropland is not greatly affected by changing tillage practices (Wu et al., 2004). Tillage is much more effective at controlling sediment loss than nutrient loss.
- The net social cost to both producers and consumers of reducing edge-of-field nutrient loss from cropland in the MARB by 20 percent was estimated to be $1.02 billion (2015 dollars) per year (Doering et al., 1999). This is the only study that allows commodity markets to adjust to the production shocks created by having to meet nutrient-reduction goals, but it does not estimate impacts on nutrient delivery to the Gulf.

Scenarios

We evaluate two scenarios representing alternative structures of a policy constraint on nutrient discharge:

- Meeting a 45-percent reduction in total nitrogen and phosphorus loads from cropland delivered to the mouth of the Mississippi River (***Gulf Constraints scenario***). We selected this goal based on estimates in the literature of what might be required to meet the Gulf Hypoxia Task Force goal. We refer to this scenario as the “cost-effective” scenario in meeting the Gulf hypoxia target, as it generates the least-cost changes in land use and cropland management across the entire MARB. Within this scenario, we assume a full range of on-field practices, riparian buffers, restored wetlands, crop rotations, and land retirement are available to producers to meet nutrient loss constraints.

- Requiring that each of the production regions within the MARB reduce discharges of nutrients to ground and surface waters by 45 percent, which results in a reduction in loads to the Gulf by 45 percent as well (***Regional Constraints scenario***). This represents a scenario where the nutrient-reduction goals (in percentage terms) are distributed more equally across sub-basins, potentially addressing both local and Gulf water quality goals.

Models and data

The agronomic and economic impacts of the scenarios are estimated with the ERS Regional Environment and Agriculture Programming (REAP) model, a mathematical optimization model that quantifies production of 10 major commodity crops (corn, sorghum, oats, barley, wheat, rice, cotton, soybeans, hay, and silage) and the associated environmental impacts for 273 production regions across the United States (Johansson et al., 2007). The basic unit of crop production activity in REAP is a crop production enterprise, which refers to a specific combination of crop rotation, tillage, and irrigation. REAP allocates production acreage among a discrete set of crop production enterprises available to each region and distributes 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 (consumer and producer surpluses). See Appendix 1 for more information on REAP's structure and optimization process.

Changes in cropland nutrient loss could be generated in the basic REAP model through regional changes in cropping mix and crop rotations, tillage systems, or cropland fallowing and retirement. For this project, we greatly expanded the management options available to farmers in the model for reducing nutrient loads to water resources. From the USDA Conservation Effects Assessment Project (CEAP) we obtained data on a set of practices for improving nutrient management and reducing field-level losses (see box, "Conservation Effects Assessment Project"). These practices include nutrient management, cover crops, drainage water management, erosion controls, enhanced nutrient management (nutrient management plus structural erosion controls), cover crops plus structural erosion controls, and drainage water management plus structural erosion controls. See Appendix 2 for details on how the CEAP data were introduced into the REAP modeling framework.

The REAP model was further enhanced by including two off-field practices that intercept and filter nutrient runoff from fields: riparian buffers and restored wetlands. Potential expansion in streamside buffer area and associated treatment area in the MARB was estimated from spatial data coverages from the USDA's National Agricultural Statistics Service (NASS) Cropland Data Layer, the USDA's Farm Service Agency (FSA) Common Land Unit Dataset, and the U.S. Geological Survey's National Hydrography dataset. Wetland restoration area was limited to ~389,000 acres of tile-drained cropland, or about 1 percent of total tile-drained cropland in the MARB reported in the 2012 Agricultural Census. Each acre of restored wetland was assumed to be optimally located and to treat the runoff from 18-25 acres of cropland, depending on the region. For more information, see Appendix 3, "Riparian Buffers and Wetland Restoration—Data and Modeling Assumptions."

Conservation Effects Assessment Project

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 covering the entire MARB (Upper Mississippi, Lower Mississippi, Ohio-Tennessee, Missouri, and Arkansas-White-Red) was conducted as part of CEAP to assess the water quality benefits from conservation systems (USDA NRCS, 2011, 2012a, 2012b, 2013a, 2013b).

The National Resources Inventory (NRI)—a periodic 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 for the CEAP studies. A subset of NRI sample points on cultivated cropland and land in long-term conserving cover was selected to serve as "representative fields." Field-level surveys conducted on these sample points over 2003-06 collected information on production systems in use between 2001 and 2006. The survey data were then used to design a set of simulation analyses exploring the potential nutrient implications of adopting additional conservation practices on those surveyed points (USDA NRCS, 2011, 2012a, 2012b, 2013a, 2013b).

Field-level effects of conservation practices and input use (including both commercial and manure nutrients) were assessed in CEAP using the Agricultural Policy Environmental Extender (APEX) model (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 of management choices. Weather largely determines the emission levels 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 crop growth simulations and are treated as long-term averages. Deliveries of nutrient discharges from the edge of field to subwatershed outlets and then to the Gulf were estimated using delivery coefficients derived from the Soil and Water Assessment Tool (SWAT) that account for instream pollutant fate and transport losses (White et al, 2014) (See box, "Instream Nutrient Eelivery Ratios").

In addition to implementing new conservation systems on working cropland, cropland can be removed from production and either converted to permanent conservation cover under the Conservation Reserve Program (CRP) or fallowed. For a discussion of nutrient control measures addressed in the analysis, see box, "Conservation Systems for Reducing Nutrients."

Conservation Systems for Reducing Nutrients

The following are the management systems included in the CEAP data, along with the assumptions made for the CEAP simulations.

Cover crops—Cover crops are planted after the principal crop has been harvested to provide soil surface cover, reduce soil erosion, and remove nutrients remaining in the soil, preventing them from leaching or running off to surface water. In this analysis:

- For sample points in the baseline without a cover crop in the rotation, rye is planted as the cover crop.
- The cover crop is planted the day after harvesting the main crop, or the day after the last major fall tillage practice.
- The cover crop is not harvested for sale. Plant residue is left on the field surface or incorporated into the soil.

Nutrient management—Nutrient management is defined in terms of the appropriate rate, timing, and method of application for all crops in the rotation. In this analysis:

- All commercial fertilizer and manure applications occur within 3 weeks prior to plant date, at planting, or within 60 days after planting.
- The method of application for commercial fertilizer or manure is some form of incorporation, banding (incorporating nutrients into the soil immediately adjacent to plants), spot treatment, or foliar application (applying nutrients directly on plants).
- The rate of applied nitrogen, including the sum of both commercial fertilizer and manure nitrogen available for crops in the year of application, is—
  - less than 1.4 times the amount of nitrogen removed in the harvested yield for each crop, except for cotton and small grain crops;
  - less than 1.6 times the amount of nitrogen removed in the harvested yield for small grain crops (wheat, barley, oats, rice); and
  - less than 60 pounds of nitrogen per bale of cotton harvested.

- The rate of applied phosphorus summed over all applications and crops in the rotation, including both commercial fertilizer and manure phosphorus, is less than 1.1 times the amount of phosphorus removed in the crop yields at harvest summed over all crops in the rotation.

Drainage water management—DWM is a management practice that adjusts or controls depth to water table within a subsurface tile drainage system. Reducing drainage at certain times of the year raises the water table, thus increasing nitrogen losses to the atmosphere (denitrification) and reducing the amount of nitrogen entering streams. This is accomplished by installing a flow control mechanism on tile lines or drainage ditches. In this analysis, flow control mechanisms

—continued

Conservation Systems for Reducing Nutrients—continued

are installed on tile-drained cropland to control field water levels. DWM only affects the field it is used on.[2]

Erosion controls—Water-erosion controls reduce the loss of nutrients attached to soil particles (primarily phosphorus) by reducing field slopes, reducing the length of time a field is without plant cover, or trapping sediment in runoff. In this analysis:

- Terraces are added to all sample points with slopes greater than 6 percent, and to those with slopes greater than 4 percent and a high potential for excessive runoff (hydrologic soil groups C or D).
- Contouring or strip-cropping is added to all other fields with slope greater than 2 percent that do not already have those practices.
- Fields adjacent to water receive a riparian buffer.
- Fields not adjacent to water receive a filter strip.
- No changes are made to tillage.

Other practices included in our analysis that can affect nutrient losses include:

Tillage—Mechanically turning over the soil is a traditional method for controlling weeds, speeding the decay of crop residues, and easing planting operations. We define two categories of tillage: conventional tillage and conservation tillage (crop residue left on fields). While conservation tillage primarily addresses soil erosion and soil health (by increasing soil organic matter), it also influences the movement of nutrients. Conservation tillage systems reduce soil erosion and particle-associated nutrients, primarily phosphorus. However, they may also increase dissolved nutrient losses through subsurface flow (Dodd and Sharpley, 2016; Kleinman et al., 2011; Sharpley et al., 2002; Sprague and Gronberg, 2012).

Rotations—Crop rotations refer to the sequence of crops planted on a field over a number of growing seasons. Since crops vary in their nutritional needs, nutrient applications and potential nutrient losses vary by crop choice. Introducing a crop with low nutrient needs such as soybeans or wheat into what was a continuous corn rotation (a high nutrient-need crop) would reduce the average loss of nutrients from the field without any additional nutrient management practices. Economically feasible crop rotations at a particular location depend on climate and soils.

Land retirement—Nutrient loss could be reduced by removing cropland from production. It may be more economical to remove marginal cropland characterized by low yields and high production costs than to implement nutrient management practices on highly productive cropland. The model includes retired land enrolled under USDA's Conservation Reserve Program

—continued

---

[2] The timing of peak drainage and of drainage management efforts varies regionally and may influence how effective drainage water management is at reducing nutrient loads when they are most critical for Gulf hypoxia. Because REAP optimizes over annual conditions, we are not able to take seasonal timing considerations into account in our analysis.

Conservation Systems for Reducing Nutrients—continued

(CRP), which provides for a rental payment and practice cost-share payments to participants in return for long-term conservation covers on environmentally sensitive land.[3]

Restored wetlands—Constructed or restored wetlands can be effective at removing nitrates from water, primarily through denitrification. In the CEAP model, we take drained cropland out of production and convert it to a wetland for the purpose of filtering nitrogen and phosphorus. Wetlands vary in effectiveness, and the most effective use of this practice will likely be limited to areas in the MARB that were once wetlands and are productive in agriculture only through artificial drainage. Our analysis limits the potential extent of restored wetlands by assuming that only optimal wetland sites are used. We estimate that potential area as roughly 1 percent of the total tile-drained cropland in the MARB reported in the 2012 Census of Agriculture, capping restorable wetland extent at ~389,000 acres within the MARB. The production area treated by those wetlands, however, is much larger, as we assume a wetland-to-treatment area ratio that varies by region, between 1:18 and 1:25 (see Appendix 3 for more details).

Riparian buffers—Areas of herbaceous or forest vegetation established along permanent or intermittent water courses help to stabilize stream banks, reduce soil erosion, and remove nutrients from water. Nitrate is removed through plant uptake and denitrification. In our analysis, we allow for buffers installed on streams adjacent to cropland, and we assume they are 30 meters wide on both sides of the stream.

We further assume that in the case of tile-drained cropland, riparian buffers have no effect in reducing nutrient loss via subsurface tile drainage flows (see Appendix 3 for more details).

Cost of conservation systems

The CEAP data provide estimates of per-acre costs for each of the field practices included in their simulation results. The estimated costs of implementing a conservation system include capital costs (annualized over the life of the practice), annual implementation (input) costs, and the value of changes in inputs and crop yields (which generate changes in net returns).[4] Crop yields may increase or decrease, depending on the location and the rotation to which the practice is applied. On fields where manure is applied, the cost of implementing a nutrient management best management practice (BMP) grows by 20 percent. For practices that are implemented in tandem (nutrient management plus erosion controls, drainage water management plus erosion controls, and cover crops plus

---

[3] The CRP includes both a General Signup for larger land tracts under a competitive bidding process and a Continuous Signup for eligible practices on partial-field parcels. The REAP analysis does not separately model acreage in General and Continuous Signups under the CRP. We assume that Continuous Signup acreage in buffers and wetlands remains constant (i.e., no change in upslope treatment benefits relative to baseline conditions), while CRP movement involves shifts in General Signup enrollment.

[4] The full costs of implementing a conservation system, and of participating in a conservation program, would also likely include costs associated with information gathering, technical assistance, paperwork, enforcement, and monitoring. Those costs are not included in this analysis. Furthermore, the costs of practice implementation in the REAP analysis were not adjusted to reflect financial assistance available through USDA conservation programs.

erosion controls), costs reflect implementation as a single practice, rather than the summed costs of implementing practices separately.

The costs of riparian buffers are derived from reported State-level costs for USDA's Environmental Quality Incentives Program (EQIP), while wetland restoration costs are estimated based on USDA Wetland Reserve Program (WRP) contract records (for more information, see Appendix 3). With riparian buffers and wetland restoration, crop yields on the land taken out of production go to zero. However, in response to such set-asides for conservation purposes, REAP may expand production elsewhere within the region to maintain production levels. To prevent unlimited expansion, all REAP production regions have a cap on cropland availability calculated from the 2007 Agricultural Census.[5]

The costs of land retirement, changes in crop rotation, and changes in management systems are calculated within the REAP modeling system using a combination of information at scales varying from field to region to national market. At the field scale, changes in inputs and field operations associated with different crops and production systems are captured by the different operation costs associated with each production enterprise. At the regional scale, changes in land use, including land retirement, influence regional land-supply costs. At the market scale, changing crop production levels and changing prices influence both producer and consumer welfare.

When constraints on allowable nutrient delivery to the Gulf are imposed, REAP allocates production enterprises and nutrient-reduction measures within the MARB to minimize the total economic cost to producers and consumers. Nutrient deliveries to the Gulf are calculated using delivery ratios that represent the share of field-level nutrient losses that reaches the Gulf from each production region. These ratios are calculated separately by nutrient (see box, "Instream Nutrient Delivery Ratios").

Results from REAP represent long-term equilibrium solutions. As such, they do not capture adoption pathways for management changes or maturation of practices such as wetlands, which take time to become fully functional. Similarly, this approach does not consider the length of time required for biophysical systems, including nutrient flows and cycles, to reach a new equilibrium under an adjusted set of crop and land-use management patterns. Given the potential for lengthy nutrient transit times from field to Gulf, loadings will not react instantly to changes in landscape practices; our approach does not address response delays associated with such "legacy loads."

Instream Nutrient Delivery Ratios

Of the total quantity of nutrients discharged from farm fields to local waterways in the Mississippi/Atchafalaya River Basin (MARB), only a portion actually reaches the Gulf of Mexico. Instream loss and sequestering of nutrient discharges from farmland are an important consideration in assessing the contribution of regional nutrient loadings to the Gulf and the cost-effectiveness of hypoxia control strategies. Nutrient reductions from waterways may occur through uptake for aquatic and riverine biomass growth, particulate settling and burial, floodplain storage, and

—continued

---

[5] Includes all acreage in modeled and nonmodeled field crops, cropland pasture and hay, and cropland fallowed; excludes permanent pasture/rangeland and woodland pasture.

Instream Nutrient Delivery Ratios—continued

denitrification. The complexity of processes reflects the diverse hydrologically-linked zones that impact nutrient fate—including stream channels, lakes and reservoirs, riverine areas, floodplains, and conjunctive groundwater systems—and nutrient cycling dynamics that occur both temporally and spatially (Bouwman et al., 2013).

In general, nutrient removal rates increase with distance transported. Nutrient sources further upstream in the MARB generally deliver smaller nutrient loads to the Gulf. The size and depth of waterways are also important determinants of instream nutrient reductions. Nutrient removal rates are typically higher on smaller, shallower waterways—and particularly for nitrogen, reflecting increased rates of denitrification and terrestrial biomass uptake (Preston et al, 2011). Larger waterways have generally lower removal rates, especially where channelization has reduced connectivity with riparian floodplains. Thus, nutrient discharges from agricultural areas in close proximity to the Mississippi River are subject to generally reduced instream losses, relative to nutrient discharges in more distant tributaries (White et al., 2014). Dams may block the transport of larger organic matter particles while removing suspended sediments and nutrients from the water column. Dam development appears to have increased nutrient removal rates along portions of the Missouri, Tennessee, Red and Arkansas River sub-basins (White et al., 2014).

For this analysis, nutrient delivery ratios for N and P were estimated using a two-step process. First, regional delivery ratios were calculated by 4-digit Hydrologic Unit Code (HUC), based on the ratio of reported nutrient losses from fields within the HUC4 to nutrients leaving the HUC4 outlet (obtained from each of five CEAP basin reports that comprise the MARB study area). Second, CEAP delivery ratios for N and P, estimated from the HUC4 outlet to the Gulf of Mexico, were obtained directly from USDA's Agricultural Research Service (White et al., 2014). Combining the two sets of nutrient delivery ratios—(1) edge-of-field to HUC4 outlet, and (2) HUC4 outlet to the Gulf of Mexico—produces a ratio of field nutrient loss to Gulf nutrient loadings that is applied to all REAP model regions located within the HUC4 sub-basin. While nutrient delivery ratios vary widely across the study area, phosphorus removal rates during transit exceed (or nearly approximate) nitrogen removal rates for the large majority of REAP model regions.

Chapter 3: Characterizing the Baseline and Conservation Practices in the Mississippi/Atchafalaya River Basin

The cost of meeting hypoxia goals for the Gulf of Mexico will depend on changes in regional land use, cropping patterns, and management practices relative to baseline conditions. REAP's baseline is designed to approximate production patterns in the year 2007 (see box, "Baseline Year"). The MARB study area contains 237.8 million acres of cropland (defined as land in a crop rotation), with the Missouri (38.5 percent) and Upper Mississippi (27.6 percent) sub-basins containing the largest shares of cropland (figure 3.1). Corn (34.6 percent of cropland acres), soybeans (23.1 percent), wheat (18.0 percent), and hay (16.6 percent) are the four dominant crops. About 12 percent of cropland is irrigated, and 29 percent is classified as highly erodible land (HEL). Tillage systems vary across the watershed, with about 38 percent of cropland in conventional tillage, 41 percent in reduced tillage, and 21 percent in no-till.

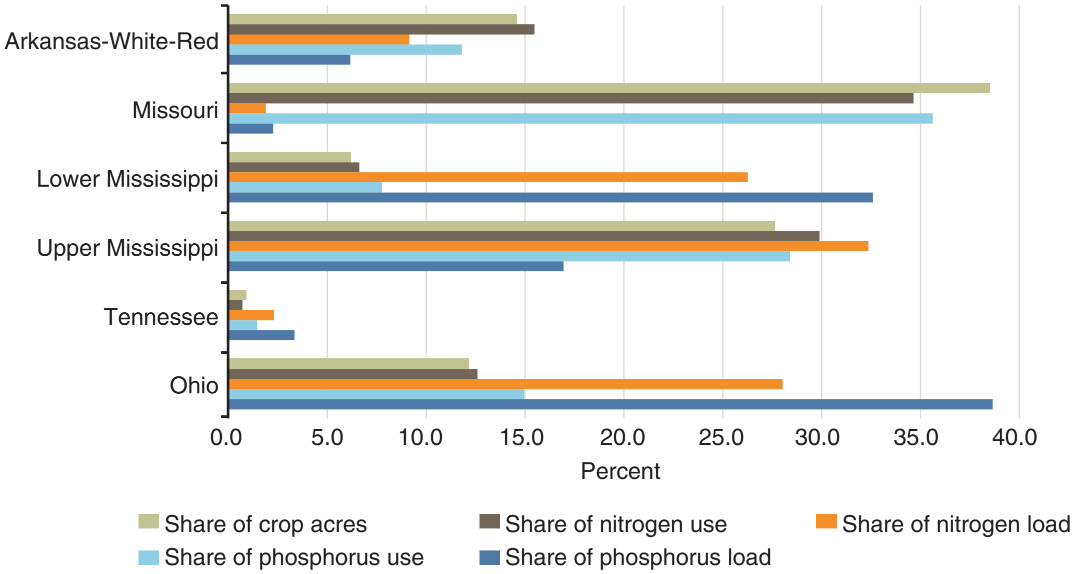
Baseline Year

Simulation modeling of the agriculture sector requires a large amount of input data to fully represent the system of interest. This analysis requires input information on baseline crop and rotation acreage, the spatial distribution of other production characteristics such as tillage and irrigation, yields and environmental impacts, feasible available alternative production methods, and the potential impacts associated with changing production methods or applying new conservation practices over a large geographic area. The most comprehensive available data at the onset of this project on potential impacts of conservation practices across the MARB study region were CEAP's simulation analysis of 2003-06 data on conservation practice coverage and cropland nutrient losses within the Mississippi/Atchafalaya River Basin (MARB); for consistency, the remaining model data drawn from public data sources (such as USDA's National Agricultural Statistics Service and the Natural Resources Institute) were compiled to represent a baseline that approximates conditions in 2007. The findings of interest for this study, however, are generally derived from the relative distribution of cost and impacts of production and production changes over the landscape, which are expected to be relatively robust to selection of a baseline year. While changes have occurred since 2007 across several of the input dimensions, including adjustments in the amount of baseline acreage employing each conservation practice, it is assumed that large shifts in the fundamental dynamics underlying the regional economic and biophysical impacts captured in this analysis are unlikely.

The baseline assumptions about nutrient loss used in this analysis are formulated by calibrating REAP's existing estimates for average nutrient loss by region to the baseline nutrient loss numbers in the CEAP analysis (see Appendix 2 for details). Based on the resulting regional estimates of nutrient loss and nutrient delivery ratios from ARS, the Upper Mississippi, Ohio, and Lower Mississippi sub-basins deliver the highest N and P loads to the Gulf (figure 3.1). The Missouri River basin contributes the least, despite its large share of total nutrient applications in the MARB. These findings are consistent with results reported elsewhere (Robertson and Saad, 2013).

Figure 3.1

Baseline acreage, nutrient use, and nutrient loadings by sub-basin*



*REAP's baseline is designed to approximate production patterns in the year 2007.
Source: USDA, Economic Research Service, Regional Environment and Agriculture Programming (REAP) model.

The costs, effectiveness, and potential for scale of adoption for each of the BMPs vary widely by region. Those differences will be a critical factor in determining the cost-effective portfolio of strategies necessary to achieve the Gulf hypoxia goals. To explore and illustrate the variation in costs and potential application and efficacy across practices and regions, we used the REAP model to simulate full adoption of each BMP individually. These simulations do not constrain either N or P loadings, nor do they include an optimization component. Instead, they fix cropland and crop rotation acreage levels and then impose each BMP individually across all REAP production enterprises for which that BMP has been designed, based on information contained within the CEAP dataset. For wetlands and buffers, those conservation practices are established on the maximum amount of acreage assumed to be available and effective for the purposes of filtering nutrients (see Appendix 3 for details). This method isolates the potential impacts of each conservation practice on reducing the discharge of N and P from each REAP production region, as well as on the aggregate and regional loadings of N and P to the Gulf. The results are then used to illustrate average unit costs of nitrogen reduction for each of the field-level practices, along with wetlands and buffers. Unit costs are important in determining the cost-effective pattern of mitigation practices adopted under the optimization results in Chapter 4.

Scale of treatment and efficacy by conservation practice

The scale at which different practices can be deployed, and their effectiveness at nutrient reduction, varies widely. Establishing wetlands and buffers requires specific hydrological conditions and positioning in order to effectively filter nutrients lost from working fields. The total acreage that can be converted to wetlands and buffers is therefore relatively small. These practices, however, have a treatment area that extends well beyond the extent of acreage placed in the wetland or buffer. In contrast, nitrogen management and erosion control can be adopted widely across the MARB, but the benefits of these BMPs are highly localized. The scale of adoption for managing drainage water is limited by the fact that it is only applicable to tile-drained acreage. In addition to the extent of area that may be treated by a given management practice, potential nutrient reductions are a function of both (1) the quantity of nutrient losses treated by a given practice and (2) the efficiency of alternative practices in controlling for nitrogen and phosphorus losses.

None of the practices alone are capable of achieving the Gulf hypoxia goals of a 45-percent reduction in both N and P delivered. When applied individually, widespread adoption of (1) nutrient management in combination with erosion control or (2) cover crops in combination with erosion control hold the greatest potential for reducing N (32-38 percent) and P (26-29 percent) (table 3.1). These practices can be applied widely and, on average, are effective at reducing both N and P. Buffers and wetlands, on the other hand, have more limited application and are generally less effective at reducing P than at reducing N over the long term.

Table 3.1

Maximum acreage and nutrient reductions associated with the on- and off-field conservation practices in this analysis

	Buffers	Wetlands	Cover crops	Drainage water mgmt.	Nutrient mgmt.	Structural erosion control	Nutrient mgmt. + erosion control	Cover crops + erosion control	Drainage water mgmt. + erosion control
Reductions in N loading to Gulf (%)	-5.87	-1.87	-20.66	-6.68	-16.69	-12.56	-32.11	-37.75	-17.82
Reduction in P loading to Gulf (%)	-1.89	-0.33	-16.93	0.21	-16.59	-17.55	-29.06	-25.58	-10.48
Acreage applied (millions)	7.59	0.39	107.77	77.50	176.91	180.52	180.74	107.77	77.50
Acreage treated (millions)	51.73	9.38	107.77	77.50	176.91	180.52	180.74	107.77	77.50

N = nitrogen; P = phosphorus.
Source: USDA, Economic Research Service calculations with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Of course, the true potential of each practice will also depend on the costs of establishing and maintaining that practice on the landscape. To estimate an average cost of N reductions from each sub-basin for each practice, we divided the total cost of applying each practice within a region by the N reduction from that region. While costs vary both within sub-basins (i.e., across production regions) and, in the case of field-level practices, across production enterprises, these averages reflect broad differences in cost that are relevant to the task of selecting a cost-effective portfolio of strategies for hypoxia mitigation. For our study, cost-effectiveness is measured as the cost of practice installation and maintenance per unit of nutrient delivery reduction achieved at some targeted spatial scale—either the Gulf of Mexico or more regionally. For conciseness, the following discussion focuses on the cost of N reductions.

Wetlands are a cost-effective option for reducing nitrogen discharge

The costs of reducing nitrogen discharge from the MARB sub-basins vary significantly among practices, but wetlands are generally a cost-effective choice when they can be implemented, given our assumptions about nitrogen removal efficiency (see Appendix 3 for more detail). However, the extent to which wetlands can be restored across the landscape is likely to be limited, as would be wetlands' practical contribution to nutrient reduction in the MARB. That result is sensitive to the assumptions we make in our analysis about the feasible extent of wetland restoration.

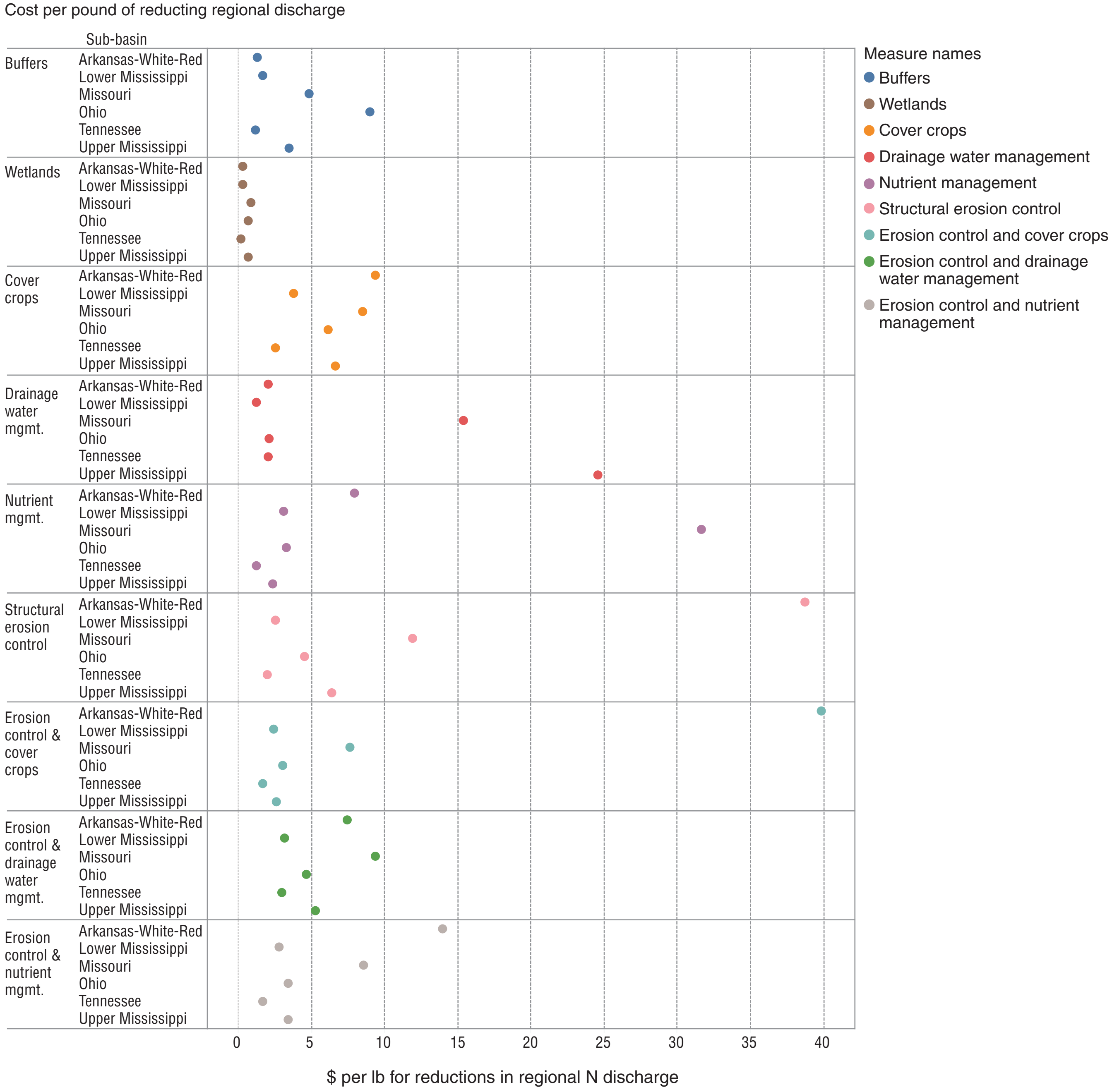
In four out of six sub-basins, drainage water management, buffers (five sub-basins), and nutrient management strategies (with and without erosion controls) are also relatively cost-effective (< $5 per pound of N reduction) in reducing nitrogen loadings, as are cover crops when combined with structural erosion-control practices. The costs per pound of reducing N discharge are generally low in the Tennessee sub-basin and relatively high in the Missouri and the Arkansas-White-Red sub-basins (figure 3.2). These results are consistent with the relatively high baseline estimates for per-acre edge-of-field nutrient loss in the Tennessee sub-basin (which could suggest a high potential to reduce losses at low cost) and the relatively low baseline nutrient loss estimates for the Missouri and Arkansas-White-Red sub-basins (figure 3.3). Per-unit reduction costs reflect the fact that costs for additional conservation practices are likely to be higher in those regions where significant gains have already been achieved—i.e., the Missouri and Arkansas-White-Red sub-basins—and where low-cost practices are already in place in the baseline.

Delivery ratios contribute to regional cost-effectiveness in reducing N loadings

Per-unit costs of reducing nutrient loadings to the Gulf are highly sensitive to where in the MARB the practices are applied. The Lower Mississippi sub-basin has the lowest cost per unit of reduction in N to the Gulf for almost every practice (table 3.2), largely due to proximity and the resulting high nutrient delivery ratio. Regions farther from the Gulf have lower delivery ratios; nutrients leaving those regions have a greater transit distance and a higher likelihood of being removed through reservoir retention, uptake by vegetation, denitrification, or particulate settling. Regions farther from the Gulf must therefore reduce nutrient discharges by a proportionately larger amount in order to reduce the amount of nutrient arriving at the Gulf by a fixed amount, leading to higher per-unit costs of reducing Gulf loadings.

Figure 3.2

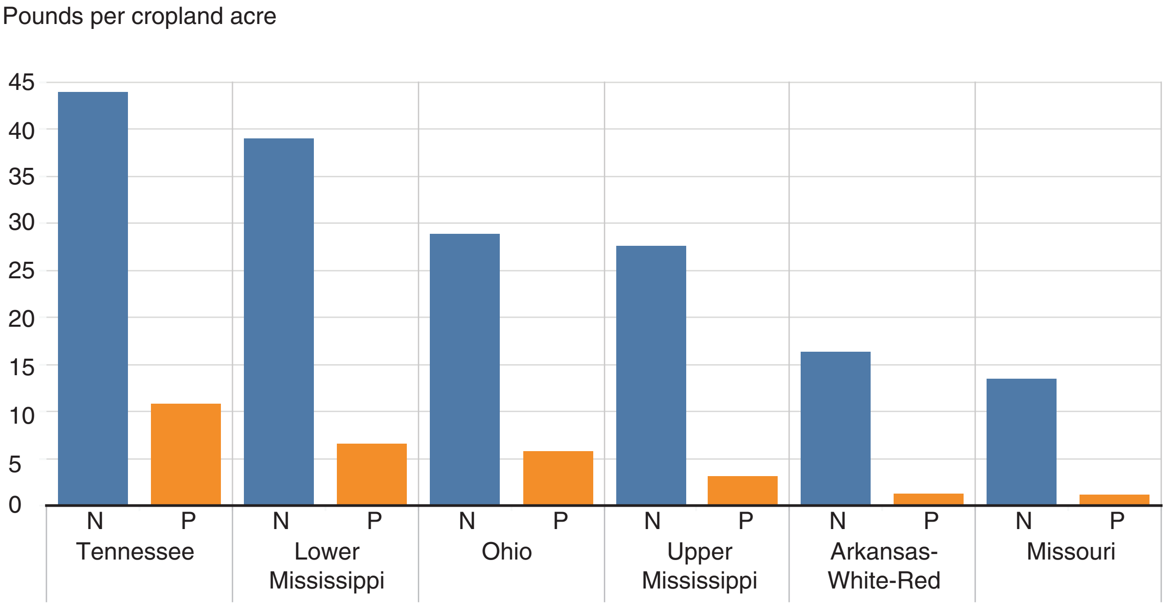
Cost-effectiveness of management practices for reducing nitrogen (N) discharge, by practice and sub-basin



Source: USDA, Economic Research Service calculations with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Figure 3.3

Average baseline nutrient loss per acre of cropland, by sub-basin



Notes: N = nitrogen; P = phosphorus.
Source: USDA, Economic Research Service calculations with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Table 3.2

Cost-effectiveness of management practices for reducing N delivered to the Gulf, by practice and sub-basin

Best management practice	Sub-basin	Cost of N reduction delivered to the Gulf ($/lb)
Wetland	Lower Mississippi	0.47
Wetland	Tennessee	0.49
Wetland	Arkansas-White-Red	0.89
Wetland	Ohio	1.28
Drainage water management	Lower Mississippi	1.73
Buffers	Lower Mississippi	2.36
Wetland	Upper Mississippi	2.85
Buffers	Tennessee	3.21
Nutrient management	Tennessee	3.32
Cover crops w/erosion controls	Lower Mississippi	3.35
Erosion controls	Lower Mississippi	3.56
Drainage water management	Ohio	3.77
Nutrient management w/erosion controls	Lower Mississippi	3.96
Nutrient management	Lower Mississippi	4.34

—continued

Table 3.2

Cost-effectiveness of management practices for reducing N delivered to the Gulf, by practice and sub-basin—continued

Best management practice	Sub-basin	Cost of N reduction delivered to the Gulf ($/lb)
Drainage water management w/erosion controls	Lower Mississippi	4.42
Cover crops w/erosion controls	Tennessee	4.44
Nutrient management w/erosion controls	Tennessee	4.50
Buffers	Arkansas-White-Red	4.93
Cover crops	Lower Mississippi	5.29
Erosion controls	Tennessee	5.41
Drainage water management	Tennessee	5.51
Cover crops w/erosion controls	Ohio	5.58
Nutrient management	Ohio	6.03
Nutrient management w/erosion controls	Ohio	6.25
Drainage water management	Arkansas-White-Red	6.59
Cover crops	Tennessee	6.89
Drainage water management w/erosion controls	Tennessee	8.03
Nutrient management	Upper Mississippi	8.31
Erosion controls	Ohio	8.45
Drainage water management w/erosion controls	Ohio	8.46
Cover crops w/erosion controls	Upper Mississippi	9.64
Cover crops	Ohio	11.22
Nutrient management w/erosion controls	Upper Mississippi	12.26
Buffers	Upper Mississippi	12.27
Buffers	Ohio	16.61
Drainage water management w/erosion controls	Upper Mississippi	18.91
Drainage water management w/erosion controls	Arkansas-White-Red	22.55
Erosion controls	Upper Mississippi	23.25
Cover crops	Upper Mississippi	23.40
Cover crops	Arkansas-White-Red	30.78
Nutrient management	Arkansas-White-Red	32.78
Wetland	Missouri	40.51
Drainage water management	Upper Mississippi	45.74
Nutrient management w/erosion controls	Arkansas-White-Red	55.48
Cover crops w/erosion controls	Arkansas-White-Red	123.46
Erosion controls	Arkansas-White-Red	142.97
Buffers	Missouri	186.72
Cover crops w/erosion controls	Missouri	321.71
Cover crops	Missouri	353.27
Nutrient management w/erosion controls	Missouri	357.81

—continued

Table 3.2

Cost-effectiveness of management practices for reducing N delivered to the Gulf, by practice and sub-basin—continued

Best management practice	Sub-basin	Cost of N reduction delivered to the Gulf ($/lb)
Drainage water management w/erosion controls	Missouri	392.47
Erosion controls	Missouri	519.65
Drainage water management	Missouri	565.42
Nutrient management	Missouri	895.46

N = nitrogen.

Source: USDA, Economic Research Service calculations with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

While reducing nutrient loadings to the Gulf from more distant regions may come at a higher cost, such reductions are likely to benefit water quality throughout the watershed as they would reduce nutrient concentrations within distant production regions as well as at every transport point between field and Gulf. Impaired water quality is a serious issue throughout the MARB. In 2011, the U.S. Environmental Protection Agency's Wadeable Streams Assessment reported that in the Upper Mississippi sub-basin, 50 percent of wadeable streams have high nitrogen levels, while in the Ohio sub-basin, 55 percent of stream miles are affected by high nitrogen and 43 percent by high phosphorus (EPA, 2011). In addition to threatening recreational use and aesthetic value of local water bodies, high levels of nutrients impair the ecological health of streams and lakes, damaging habitat and, in extreme cases, creating eutrophic conditions that can be fatal for fish and other aquatic species. We therefore distinguish between "local" water quality improvements, which occur at points throughout the MARB, and Gulf improvements, which are measured exclusively as changes in nutrient loadings to the Gulf. An assessment and valuation of those localized water quality improvements and the extent to which the practices explored here can contribute to them, however, is beyond the scope of this analysis. In optimizing across production and conservation practices, our analysis focuses on the objective of reducing nutrient loadings to the Gulf.

Chapter 4: Production Response and Market Effects of Meeting Hypoxia Goals

Cost-effectively meeting the nitrogen (N) and phosphorus (P) loading constraints dictated by the Gulf hypoxia objectives calls for adoption of a suite of production and land-use changes, including shifts in the extent and mix of cropland in production, adjustments in onfield practices and crop production methods, and land-use practices such as buffers and wetlands intended to intercept nutrient losses from the field. The relative emphasis on improvements in field-level management versus shifts in cropland under cultivation may also vary regionally depending on crops grown, production methods used, and regional cost-effectiveness and applicability of best management practices (BMPs). Moreover, the optimal sector response will depend on how the nutrient-reduction goals are established and at what point within the watershed those reductions are required.

In this chapter, we report on the impacts of a 45-percent reduction in both N and P Gulf loadings that minimizes costs to producers and consumers (measured as producer plus consumer surplus[6]) under two possible policy implementation scenarios. Under the first scenario, the nutrient-reduction goals are specified as a 45-percent reduction in both N and P deliveries to the Gulf, regardless of origin ("Gulf Constraints" scenario). The second scenario, in contrast, specifies the nutrient-reduction goal as a 45-percent reduction in the amount of N and P discharged from each of 135 modeled production regions within the Mississippi/Atchafalaya River Basin, or MARB ("Regional Constraints" scenario). This stylized scenario does not necessarily reflect local policy objectives for water quality; priorities and objectives for water quality may vary regionally within the MARB, depending on local water concerns such as groundwater quality or lake eutrophication, and may not translate into a 45-percent reduction of either nutrient. However, the latter scenario achieves the same reduction in nutrients reaching the Gulf as the former scenario, spreading responsibility for those reductions more evenly among the production regions that contribute nutrients to the Gulf, thereby potentially changing the distribution of local water quality benefits achieved under the Gulf reduction policy.

A combination of strategies contributes to cost-effective reduction in nutrient loadings

The portfolio of changes necessary to cost-effectively reduce nutrient loadings to the Gulf by 45 percent, under both constraint scenarios, is summarized in table 4.1. Although production and land-use changes are estimated at the level of the REAP production region, we aggregate those results up to six watershed sub-basins within the MARB (as delineated by the two-digit hydrologic unit codes) for convenience in reporting.

---

[6] Producer surplus is the amount that producers benefit by selling at a market price that is higher than the least that they would be willing to sell for; this is roughly equal to profit. Consumer surplus is a monetary gain obtained by consumers because they are able to purchase a product for a price that is less than the highest price that they would be willing to pay.

Table 4.1

Change from baseline in cropland acreage under conservation/management systems in the MARB after meeting 45-percent reductions in nitrogen and phosphorus loads at the Gulf and within production regions

	Gulf Constraints	Regional Constraints
	Change from baseline acreage (Million acres)[1]	
Nutrient-reduction practices		
Nutrient management	20.53	26.51
Nutrient management w/erosion control	6.11	16.38
Cover crops	1.93	8.53
Erosion controls	0.26	6.11
Cover crops w/erosion controls	0.82	7.32
Drainage water management	4.58	7.18
Drainage water management w/erosion controls	1.16	2.80
Land retirement		
Conservation Reserve Program (CRP)	2.35	5.21
Idled cropland (not CRP)	8.01	20.72
Restored wetlands	0.34	0.38
Riparian buffers	1.01	3.31
Tillage system		
Conventional till	0.00	0.03
Conservation till	0.00	-0.03
Rotations		
Continuous corn	0.79	-2.69
Continuous soybeans	-0.24	-0.21
Corn-soybeans	-1.77	-4.51

[1] Numbers are expressed as changes from baseline acreage in each practice (see Appendix 2 for more details on the baseline).
Source: USDA, Economic Research Service analysis with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Adoption of field-level conservation practices

Meeting the 45-percent reduction goal under the Gulf Constraints scenario results in an additional 26.6 million acres under nutrient management (including in tandem with erosion controls) and 2.8 million additional acres planted with cover crops (including in tandem with erosion controls) over baseline levels, as well as 5.7 million additional acres under drainage water management (DWM) (table 4.1). In total, additional nutrient-reduction measures would need to be applied to about 35.4 million cropland acres. Almost all (96 percent) of this increase occurs in the Ohio, Lower Mississippi, and Upper Mississippi sub-basins. Little change in use of conservation practices occurs in the Missouri and Arkansas-White-Red sub-basins, where costs of nutrient reductions delivered to the Gulf are relatively high, due in part to lower nutrient delivery ratios from those regions and the higher costs associated with additional conservation practices in these regions.

As the Regional Constraints scenario requires all REAP production regions to meet the 45-percent nutrient-reduction goals individually, nutrient-reduction practices are adopted more widely under this scenario in regions with low nutrient delivery ratios to the Gulf relative to the Gulf Constraints scenario. In particular, the amount of cropland under nutrient-reducing conservation practices would increase significantly in the Missouri and Arkansas-White-Red sub-basins compared with the Gulf Constraints scenario, where 11.0 million and 9.1 million acres, respectively, would receive additional treatment. We project that under the Regional Constraints scenario, nutrient management would be applied to an additional 42.9 million acres MARB-wide (table 4.1). Similarly, cover crops are expected to be grown on 15.9 million additional acres and drainage water management applied to 10.0 million additional acres. Overall, in this scenario, the intensity of nutrient management activity would increase on 74.8 million acres in the MARB, or 31.5 percent of cropland area in that region, versus 14.9 percent of cropland acres when no restrictions are placed on where nutrient reductions to the Gulf must originate.

While these changes in onfield practices are effective at reducing field-level losses, they do not achieve the full 45-percent reduction under either of our analytical scenarios. The optimal portfolio of nutrient-reduction strategies under both scenarios includes additional off-field practices—wetlands and buffers—to reduce or intercept nutrient losses.

Creation of wetlands and buffers

Installation of riparian buffers and wetlands is an additional strategy producers can use to meet nutrient-reduction goals. Each of these measures involves removing cropland from production; in some regions, production can expand to compensate for the forgone production, while in other land-constrained regions the forgone production returns are a cost of nutrient abatement. In the Gulf Constraints scenario, 1.01 million acres of riparian buffers and 0.34 million acres of wetlands are projected to be installed. Most of the buffer expansion would occur in the Upper Mississippi, Lower Mississippi, and Arkansas-White-Red regions, with lesser amounts in the Ohio sub-basin. Most of the wetland expansion would occur in the Upper Mississippi and Ohio sub-basins where much of the cropland was formerly wetlands (and currently requires drainage to remain in production), with smaller areas of wetland expansion across all the other MARB sub-basins except the Missouri, which does not restore any wetland area under the Gulf Constraints scenario.

Under the Regional Constraints scenario, buffer area is projected to be over 3.3 million acres, substantially more than under the Gulf Constraints scenario. Significant expansion in buffer area (1.6 million acres) and wetland area (0.04 million acres) is expected in the Missouri sub-basin, reflecting the increase in nutrient load reductions that are required in that region. The total wetland area (0.381 million acres) is close to the total wetland acreage assumed to be restorable within the MARB (0.388 million acres); in many production regions, acreage in wetlands is constrained by the regional cap (see Appendix 3 for details).

Adjusting tillage

In this analysis, reduced tillage seems not to be a preferred practice for addressing nutrient losses. While this result is consistent with Wu and colleagues (2004) and Sprague and Gronberg (2012), factors within this analysis may underemphasize the impacts of reduced tillage on nutrient losses. In particular, we focus on water quality and do not consider nutrient loss through windborne sediment. In areas with significant wind erosion, this pathway is a significant contributor to nutrient loss, and reduced tillage might mitigate these effects. Furthermore, we do not explicitly consider sediment reduction as a water quality goal; our constraints are placed on nutrient losses rather than on sediment losses per se.

Shifting cropland acres

Cropland area in active production in the MARB declines 4.3 percent under the Gulf Constraints scenario and 10.9 percent under the Regional Constraints scenario. Reductions are due to conversions of cropland to buffers and wetlands, higher CRP enrollment, and the idling of cropland. Total CRP enrollment in the MARB increases from about 14.8 million acres to 17.2 million acres under the Gulf Constraints scenario, with CRP acreage increasing across the Ohio, Tennessee, and Upper and Lower Mississippi sub-basins and decreasing within the Missouri and Arkansas-White-Red sub-basins.[7] Increases within the MARB are offset by CRP acreage reductions in regions outside the MARB (to maintain the national cap on total CRP acreage enrollment, which we set as 24 million acres to be consistent with the 2014 Farm Bill). An additional 8.0 million acres of cropland is simply removed from production (and does not go into CRP), with 1.35 million acres going into restored wetlands and buffers.

Cropland acreage declines are substantially greater under the Regional Constraints scenario. Total CRP acreage in the MARB increases to 20.0 million acres, representing over 80 percent of total CRP acreage nationally, with acreage increases in every sub-basin except the Arkansas-White-Red. An additional 20.7 million acres of cropland is idled within the MARB, with 3.69 million going into wetlands and buffers. Regional constraints generally force increased cropland losses across the more distant sub-basins where greater reductions in nutrient loads are required. In contrast, reductions in cropland in the Lower Mississippi sub-basin are much lower under the regional constraints than they are under the Gulf constraints. Under the former constraints, cropland losses in the Lower Mississippi are only 51 percent of those experienced under the Gulf Constraints scenario.

Cropland response to nutrient constraints includes shifts in irrigated and dryland production. Irrigated cropland, which accounts for about 12.3 percent of the working-crop acreage in the MARB, accounts for 18.6 percent of the cropland decline under the Gulf Constraints scenario. This result is driven almost entirely by acreage shifts in the Lower Mississippi, where, when faced with the pressure to reduce nitrogen loadings close to the Gulf, irrigated acreage declines by 43 percent, or 2.53 million acres. While 40 percent of the acreage in the lower Mississippi sub-basin is irrigated in the baseline, 49 percent of the decline in acreage under the Gulf Constraint scenario comes from irrigated production; the potential for greater levels of nutrient loss from irrigated acreage appears to result in a slightly disproportionate reduction in irrigated acreage under that scenario. Other regions—the Upper Mississippi, the Missouri, and the Arkansas-White-Red sub-basins—actually increase their irrigated acreage by between 172,000 acres and 240,000 acres; in those regions, the potential for higher yields under irrigated cropping systems appears to dominate the land allocation decision.

Under the Regional Constraints scenario, in contrast, acreage loss slightly favors dryland production, on average, across the MARB as well as across all sub-basins except the Missouri. The higher yields in irrigated cropping systems again dominate in several regions; irrigated acreage expands across the Ohio, Upper Mississippi, and Arkansas-White-Red sub-basins. This expansion helps to offset net losses in dryland production. In contrast, disproportionate losses in irrigated acreage occur in the Missouri sub-basin, which reflects the increased pressure to reduce nutrient loss there under the Regional Constraints scenario.

---

[7] The representation of CRP in this analysis is highly stylized; the model has a national limit on total acres enrolled, but it does not differentiate between continuous enrollment and general signups, nor does it account for rules of enrollment, the bidding process, or county caps on enrolled acreage.

Cropland response also includes shifts in highly erodible and non-highly erodible cropland. Under the Gulf Constraints scenario, cropland removed from production was predominantly highly erodible in the Ohio, Tennessee, and Upper/Lower Mississippi sub-basins, where cropland losses were concentrated. These losses in highly erodible acreage were offset, however, by acreage gains in the Missouri sub-basin, which were also disproportionately on highly erodible soil, leaving the MARB-wide proportion of production on highly erodible acreage (29 percent) roughly the same. When regional constraints are included, however, land is retired across all sub-basins. That land is disproportionately highly erodible in all regions except the Lower Mississippi, where baseline cropland is only 11.6 percent highly erodible land (HEL), driven by more generalized pressures to reduce nutrient loss and generally higher rates of erosion, runoff, and nutrient loss per acre on HEL cropland.

Both the acreage and percentage of corn grown under a continuous corn rotation in the MARB increase under the Gulf Constraints scenario. Corn prices were relatively high in our analysis, and in response, the model maximizes corn production on a smaller land base. The nutrient-reducing conservation measures put in place—including offsite filtering practices such as buffers and wetlands—help offset the nutrient loading effects of a shift to more intensive corn production. More intensive corn production also occurs in parts of the MARB that have relatively low nutrient delivery ratios to the Gulf; the Missouri sub-basin increases continuous corn production by 743,000 acres, while the Arkansas-White-Red, Ohio, and Upper Mississippi sub-basins also increase continuous corn acreage but by less than 77,000 acres each. In contrast, under the Regional Constraints scenario, acreage in continuous corn rotations within the MARB is projected to drop, largely due to declines in continuous corn production in the Missouri and Arkansas-White-Red sub-basins.

Conservation strategies affect nutrient losses and nutrient loadings to the Gulf

The adoption of the strategies described above reduces applied nutrients and edge-of-field nutrient losses, as well as nutrient loadings measured at the Gulf. The distribution of those changes varies depending on how the reduction constraints are formulated.

Reductions in applied nutrients

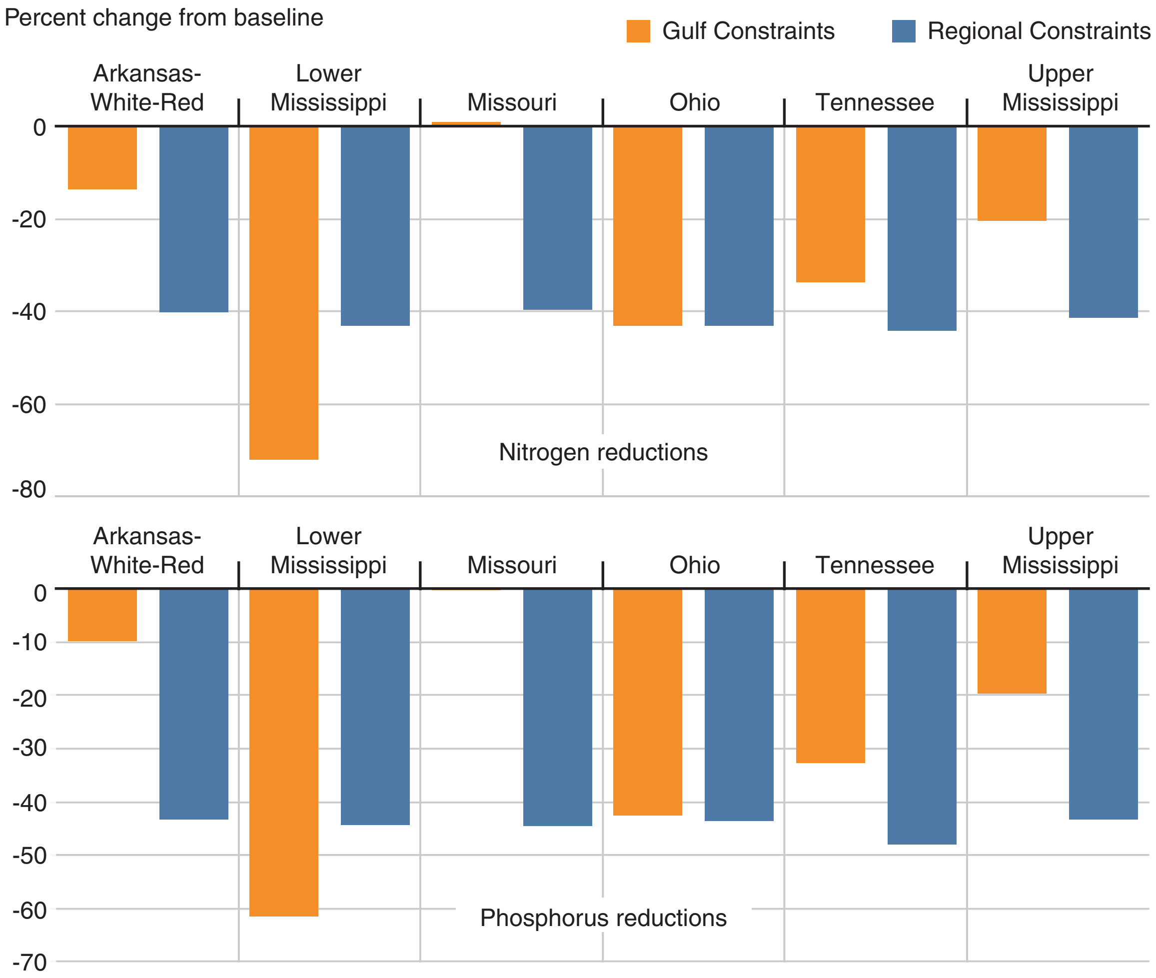
Average nutrient application rates per cropland acre generally decline across the MARB under both the Gulf and Regional scenarios, with lower application rates under the Regional Constraints than under the Gulf Constraints scenario for all MARB sub-basins other than the Lower Mississippi. This reflects the more intensive adoption of conservation practices under the Regional Constraints scenario, together with other cropping-system and land allocation adjustments that restrict aggregate levels of applied nutrients on cropland.

Edge-of-field nutrient reductions

The changes in management practices and land use translate into reductions in nutrient loads delivered from fields to water loss pathways within each sub-basin. In the Gulf Constraints scenario, the greatest percentage reductions in edge-of-field nutrient losses occur in the Lower Mississippi, Ohio, and Tennessee sub-basins (figure 4.1). The cost of reducing nutrient loads delivered to the Gulf is estimated to be generally lower in these regions, due to close proximity to the Gulf (high delivery ratios), high baseline nutrient loss per acre (or high potential to reduce losses), and greater potential to leverage low-cost practices that have not yet been adopted (figure 3.3).

Figure 4.1

Edge-of-field reductions by sub-basin under optimal production and land-use changes to meet goal of 45-percent reduction in nutrient loading



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service analysis with REAP-CEAP framework.

Under the Regional Constraints scenario, total edge-of-field nutrient reductions are projected to be higher than under the Gulf Constraints scenario for the Ohio, Tennessee, Upper Mississippi, Missouri, and Arkansas-White-Red sub-basins, as all are required to reduce nutrient deliveries to their own waters by 45 percent (figure 4.1). Additional conservation effort is required in these regions to meet this goal. Because additional nutrient reductions are being generated in these other regions, the pressure to reduce nutrients in the Lower Mississippi region declines, and reductions in edge-of-field losses in the Lower Mississippi region drop significantly.

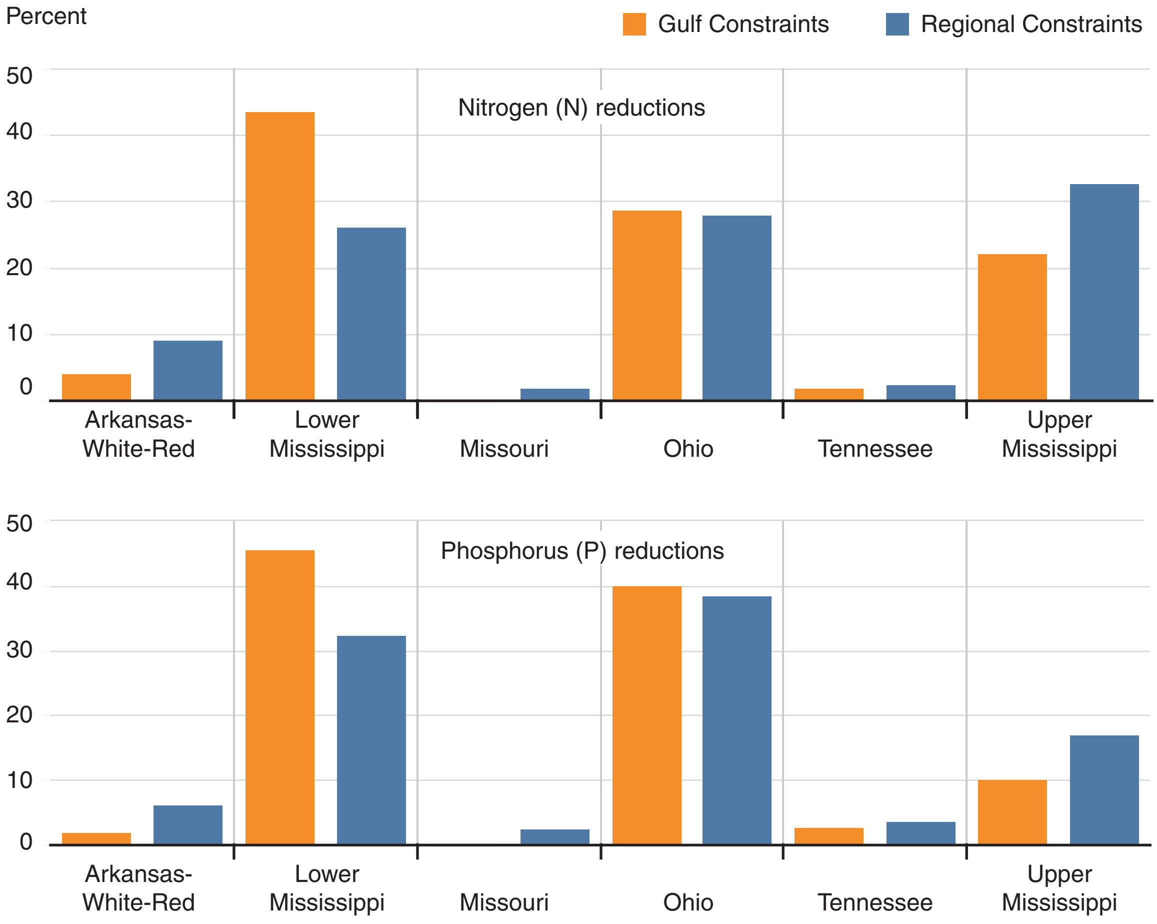
Nutrient reductions measured at the Gulf

By design, both constraint scenarios reduce N and P loads to the Gulf by 45 percent. But where would the load reductions come from? In the Gulf Constraints scenario, the greatest shares of estimated N load reductions to the Gulf come from the Lower Mississippi (43.6 percent), Ohio (28.7

percent), and Upper Mississippi (22.1 percent) sub-basins (figure 4.2). While the Upper Mississippi contributes the largest baseline share of total N load to the Gulf, its share of the total N reduction is smaller than that of either the Lower Mississippi or Ohio sub-basins when allocating nutrient reductions based on cost-effectiveness. Under this criterion, regional proximity to the Gulf outlet (higher delivery ratios) and/or lower unit costs of reducing nitrogen favors a major share of the N load reduction coming from the Lower Mississippi, which contains only 6.2 percent of the MARB's baseline cropland.

Figure 4.2

Estimated shares of load reduction to the Gulf from 45-percent constraints on N and P at the Gulf outlet and within the REAP production regions



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service analysis with REAP-CEAP framework.

In contrast, the Missouri sub-basin delivers relatively little nutrient load to the Gulf, given the distances involved, climate, and the types of crops grown (figure 3.1). Therefore, the scenario that imposes a constraint on nutrient loadings to the Gulf has very little impact on production practices in this region relative to other sub-basins in the MARB. An increase in crop prices (discussed below) is projected to lead to some intensification in production in the Missouri sub-basin, resulting in small increases in field-level losses of nitrogen and soil erosion, which lead to very small (< 1%) increases in N loading to the Gulf from this sub-basin.

Under the Regional Constraints scenario, where all production regions are required to meet the same 45-percent nutrient-reduction goal, shares of the total load reductions to the Gulf generally match the baseline shares of delivered loads, as expected.

Production adjustments and market impacts have implications outside of the Mississippi/Atchafalaya River Basin

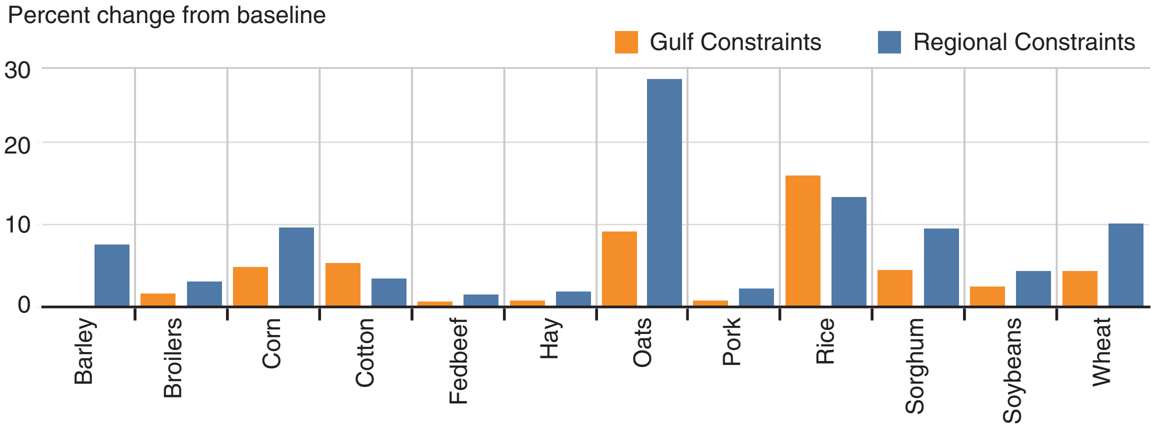
Nutrient-reduction measures implemented to meet the Gulf hypoxia goals reduce commodity production within the MARB. The market impacts associated with those production changes, however, are felt by producers both inside and outside the MARB.

Commodity prices, net returns, and consumer surplus

Changes in both crop acreage and crop yields result in supply shifts sufficient to affect crop prices (figure 4.3), which has an additional influence on production decisions both within and outside the MARB. Yields can change due to adoption of nutrient-reducing management practices, changes in tillage, changes in crop rotation, and regional shifts in where particular crops are grown. The prices of all crops except barley increase under the Gulf Constraints scenario, with prices of rice (15.8 percent), oats (9.1 percent), and cotton (5.3 percent) increasing the most. These are major crops in the Lower Mississippi sub-basin, where production changes would be most concentrated and the greatest reductions in nutrient loads to the Gulf would occur. Under the Regional Constraints scenario, when pressure on the Lower Mississippi sub-basin is relieved, the prices of rice and cotton increase by a smaller amount—13.3 percent and 3.4 percent, respectively. The prices of other crops generally increase to a greater degree, however, as more land MARB-wide undergoes changes in management or drops out of production. Prices of oats, rice, wheat, sorghum, and corn all increase more than 9 percent. Crop imports in the REAP model increase slightly in response to higher prices, while exports decline; trade is only coarsely represented in the REAP model, and the responsiveness of imports and exports is constrained to highlight domestic response and impacts.

Figure 4.3

Expected change in commodity prices from meeting 45-percent reduction in nitrogen and phosphorus loads at the Gulf and within production regions



[1]REAP (Regional Environment and Agriculture Programming) and modeling does not account for any increases in production outside the United States that could affect world prices.
Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service analysis with REAP-CEAP framework.

Increases in crop prices are a cost to consumers of crop commodities. Under the Gulf Constraints scenario, domestic consumer welfare, as measured by domestic consumer surplus, falls an estimated 2.5 percent, or $1.9 billion. Under the Regional Constraints scenario, consumer welfare drops an estimated 4.4 percent, or $3.3 billion. Those costs, however would be offset by the benefits to consumers from cleaner water; our analysis does not attempt to place a value on those benefits.

Under the Gulf Constraints scenario, meeting a 45-percent nutrient-reduction goal at the Gulf is estimated to increase producer net returns within the MARB basin by 1.3 percent, or $847 million. This result reflects the combined impacts of higher production costs from adopting conservation practices, forgone production on reduced cropland acreage, and higher crop prices from shifting patterns of production. The expected increases in commodity prices more than compensate crop producers in the MARB (as a whole) for the costs of meeting the nutrient-reduction target. However, not all crop producers would benefit. Net returns are projected to decline in sub-basins where the most significant changes in management occur. For example, net returns decrease more than 19 percent in the Lower Mississippi under the Gulf Constraints scenario (figure 4.4). In regions where fewer nutrient-reducing management changes occur, such as the Missouri sub-basin, higher commodity prices are projected to increase net returns. Modeled increases in commodity production for many crops in these regions are insufficient to make up for production losses in the regions where most of the conservation effort is focused, leading to generally higher prices.

Under the Regional Constraints scenario, net returns decrease by 0.4 percent, or $264 million. In this scenario, higher prices are offset by more extensive (required) changes in production throughout the MARB and higher per-unit costs of abatement across production regions. In this scenario, all sub-basins except the Upper Mississippi experience declines in net returns, with net returns in the Tennessee sub-basin decreasing by more than 17 percent. The Upper Mississippi, which contains large amounts of very productive cropland and is one of the major contributors of nutrients to the Gulf, sees small increases in net returns under both scenarios (2.6 percent and 2.2 percent, respectively).

Changes outside the MARB

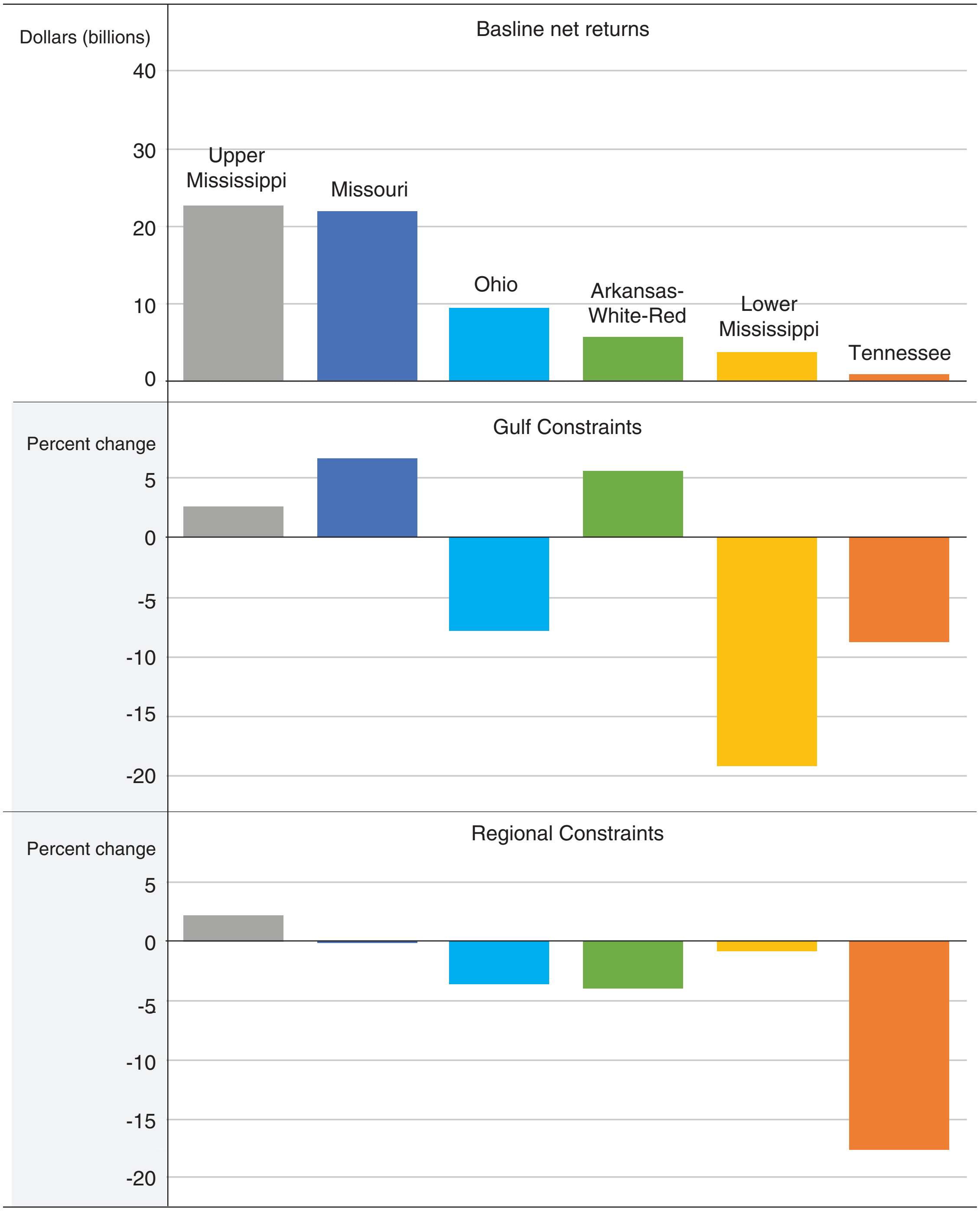
Higher crop prices result in both expanded crop acreage and increased production intensity outside the MARB, where nutrient loading is unconstrained.[8] U.S. cropland outside the MARB increases 2.1 percent under the Gulf Constraints scenario and 4.0 percent under the Regional Constraints scenario (table 4.2). As a result, edge-of-field nutrient and sediment losses generally increase in watersheds outside the MARB, particularly under the Regional Constraints scenario, assuming no changes in the effort to reduce such loads (table 4.3). Increases in pollutant loads may be of particular concern in some watersheds. For example, in the Mid-Atlantic and Great Lakes regions, extensive watershed-scale programs have been established to address nutrient pollution in the Chesapeake Bay and Lake Erie. Soil erosion in the Rio Grande and Upper Colorado sub-basins are projected to increase significantly should crop production expand onto erosive lands. Increased nutrient and sediment loads resulting from more intensive production in these regions could make achieving water quality goals costlier by requiring additional nutrient and sediment management across all sources.

---

[8] Price increases could also affect production decisions outside the United States. Modeling such international impacts, however, is beyond the scope of this analysis.

Figure 4.4

Change in total net returns to crop producers from meeting a 45-percent reduction in nitrogen and phosphorus loads at the Gulf and within production regions



Source: USDA, Economic Research Service analysis with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Table 4.2

Change in acreage of major crops from meeting 45-percent reduction in nitrogen and phosphorus loads at the Gulf and within production regions

Crop	Base	Gulf Constraints	Regional Constraints
	Million acres	*Percent change*	
Corn	95.8	-1.3	-7.9
MARB	79.6	-2.0	-10.4
Outside MARB	16.1	2.3	4.8
Hay	62.2	-3.5	-7.0
MARB	38.3	-5.7	-11.8
Outside MARB	23.8	0.2	0.8
Soybeans	63.6	-4.6	-7.2
MARB	53.2	-5.6	-8.9
Outside MARB	10.4	0.6	1.4
Wheat	58.8	-1.6	-4.9
MARB	41.5	-3.8	-10.8
Outside MARB	17.3	3.9	9.3
Total acres in crop rotations*	326.1	-2.6	-6.9
MARB	237.8	-4.4	-10.9
Outside MARB	88.3	2.1	4.0

*Total acreage also includes land in rice, oats, cotton, sorghum, barley, and silage, as well as fallow land that is part of a crop rotation.

MARB = Mississippi/Atchafalaya River Basin.

Source: USDA, Economic Research Service analysis with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Table 4.3

Change in total edge-of-field losses by sub-basin from meeting 45-percent reduction in nitrogen and phosphorus loads at the Gulf and within production regions

	Gulf Constraints			Regional Constraints		
Sub-basin	N	P	Erosion	N	P	Erosion
	Percent					
MARB						
Ohio	-43.2	-42.6	-34.1	-43.3	-43.6	-23.2
Tennessee	-33.6	-32.7	-32.5	-44.3	-47.9	-40.4
Upper Mississippi	-20.4	-19.7	-6.5	-41.4	-43.2	-30.1
Lower Mississippi	-72.2	-61.5	-73.2	-43.2	-44.2	-45.7
Missouri	1.2	-0.1	4.0	-39.7	-44.6	-23.0
Arkansas-White-Red	-13.5	-9.9	-1.7	-40.3	-43.4	-23.4
Sub-total	-24.3	-28.6	-10.8	-41.4	-43.9	-27.2
Outside MARB						
New England	0.2	0.0	0.2	0.4	0.0	0.4
Mid-Atlantic	0.4	0.3	0.1	1.0	0.7	0.4
South Atlantic-Gulf	3.7	2.5	3.8	3.5	3.2	4.3
Great Lakes	1.0	0.1	0.6	1.7	0.6	1.3
Souris-Red-Rainy	2.3	1.8	2.2	5.7	4.4	4.8
Texas-Gulf	3.5	1.1	5.4	3.8	1.5	4.4
Rio Grande	1.7	0.8	10.7	2.8	1.5	22.6
Upper Colorado	1.5	0.7	8.9	4.5	1.7	25.9
Lower Colorado	0.2	-0.5	2.2	0.2	-0.4	0.7
Great Basin	3.2	2.4	0.7	9.5	6.2	2.0
Pacific Northwest	4.9	3.1	4.1	10.3	7.2	11.1
California	1.4	1.1	0.5	1.3	1.2	0.7
Sub-total	2.2	1.2	3.5	3.4	2.3	5.0
US total	-15.1	-19.0	-6.1	-25.9	-29.0	-16.7

Source: USDA, Economic Research Service calculations with the REAP-CEAP (Regional Environment and Agriculture Programming-Conservation Effects Assessment Project) framework.

Net returns for crop producers outside the MARB increase 6.2 percent under the Gulf Constraints scenario and 11.2 percent under the Regional Constraints scenario; crop producers outside the MARB benefit from higher commodity prices, without bearing the costs of adopting conservation strategies to reduce nutrients within the MARB. For the Nation as a whole, producer net returns are estimated to increase about 2.7 percent under the Gulf Constraints scenario and 2.9 percent under the Regional Constraints scenario. However, these increased returns arise from higher prices, and higher commodity prices are a cost to consumers of crop-related products.

Chapter 5: Policy Tools for Meeting Water Quality Goals

The prior analysis estimates the least-cost allocation of conservation measures, cropping practices, and land-use changes across the Mississippi/Atchafalaya river basin (MARB) in order to meet Gulf hypoxia goals. While achieving this exact landscape of changes in cropping and nutrient management measures through current policies may be impossible, the analysis does indicate factors that can help inform those policies and improve their efficiency. In this chapter, we consider three agricultural policy instruments that have been used in prior contexts to address environmental goals—targeting, compliance, and pay-for-performance—and discuss how they might be applied to address the Gulf hypoxia challenge.

Targeting

One approach might be to target financial and technical assistance to particular conservation systems, regions, or landscape characteristics where the impact of practices is estimated to be particularly high. Targeting criteria can take multiple forms. The USDA Environmental Quality Incentives Program targets ecologically important areas (e.g., Chesapeake Bay and western Lake Erie) and incorporates ranking criteria in selecting contracts at the local level. Similarly, the USDA Conservation Reserve Program incorporates ranking criteria and designated priority areas to target conservation funding.

Various studies have explored potential targeting criteria in determining how best to allocate resources toward addressing hypoxia in the Gulf of Mexico. Our findings are consistent with prior studies emphasizing the importance of the delivery ratio, which reflects proximity to the Gulf of Mexico and the main stem of the Mississippi River, in determining nutrient loads to the Gulf (White et al., 2014; Robertson et al., 2009, 2014). White et al. (2014) identified regions within the Upper Mississippi, Lower Mississippi, and Ohio sub-basins as the major contributors to nutrient loadings in the Gulf, while Robertson et al. (2009) identified regions in the Central Mississippi, the Ohio, and the Lower Mississippi sub-basins as having the highest delivered yields. Both suggest such information could be used by managers to prioritize where conservation efforts could be targeted for optimal impact.

Our analysis expands the scope of those studies by introducing an economic element into the targeting criteria and focusing not only on where the nutrients arise but where it would be most cost-effective to reduce them. Although the Upper Mississippi contributes the greatest share of nitrogen to the Gulf, our results suggest that the Lower Mississippi sub-basin generally has the lowest cost per unit of N reduction, followed by the Ohio and Tennessee sub-basins, and that cost-effective reduction efforts could be focused there. Because Lower Mississippi farmers bear a responsibility for nutrient reductions that is disproportionate to the amount of nutrients they produce, and vice versa for the Upper Mississippi, there is a tradeoff between the cost-effectiveness criterion explored here and what could be perceived as a more equitable approach to reductions, which would spread responsibility for reductions around the MARB in proportion to the amount of nutrients delivered. Such an approach, captured in the Regional Constraints scenario, spreads reductions more broadly and generates more widespread local water benefits, but does so at a higher total cost to producers and consumers.

Our results also suggest, however, that certain practices—optimally placed wetlands in particular—tend to be more cost-effective than others, regardless of sub-basin.

A truly cost-effective targeting program would need to consider the variability of cost-effectiveness across regions and practices, and be sensitive to regional constraints on the applicability of practices such as wetlands, buffers, and drainage water management.

Nutrient compliance

Voluntary subsidy and education programs have been the primary Federal and State policy tools for promoting the adoption of nutrient-reducing management practices. Potential quasi-regulatory tools include conservation compliance requirements, which require farmers to meet federally specified standards of environmental protection on environmentally sensitive land in order to qualify for many USDA farm program benefits, including conservation and commodity program payments. Under existing conservation compliance provisions, farm program eligibility could be denied to producers who:

- Fail to implement and maintain an USDA Natural Resources Conservation Service (NRCS)-approved soil conservation system on highly erodible land (HEL compliance);
- Convert HEL grasslands to crop production without applying an approved soil conservation system (Sodbuster); or
- Convert a wetland to crop production (Swampbuster).

Farmers whose expected program benefits are subject to forfeiture and are higher than the cost of implementing conservation practices are likely to adopt the required conservation measures. Current compliance provisions have been shown to contribute to reduced soil erosion and to have discouraged the conversion of non-cropped HEL land and wetlands to cropland (Claassen et al., 2004, 2017).

In this analysis, we explore the implications for nutrient use of a hypothetical “nutrient compliance” policy. While comprehensive nutrient management considers multiple dimensions of fertilizer use, including rate, timing, source, and method of application, this analysis focuses on a single management dimension—the rate of fertilizer application. We use data from the 2012 Census of Agriculture and NASS-ERS Agricultural Resource Management Survey data from years 2002-2011 to estimate the quantity of “excess” nitrogen generated by each farm in the MARB (the REAP-CEAP framework was not used for this analysis).[9] We then consider a hypothetical nitrogen-compliance policy requiring farmers who receive Federal farm program benefits to limit nitrogen fertilizer application (organic and inorganic) to an amount deemed agronomically acceptable, given expected crop yields. See Ribaudo et al. (2017) for details about the methodology used in this section. Assessing the effectiveness of nutrient compliance at reducing excess nitrogen application in the MARB requires information on four factors:

- The incidence of excess nitrogen applications across farms in the MARB,
- Program benefits received by farms with excess nitrogen applications,
- Costs of implementing an acceptable nutrient management plan, and

---

[9] Excess is defined as the total amount of nitrogen purchased plus the amount available in livestock manure produced on the farm and applied to crops minus the amount used by crops (see Ribaudo et al., 2017). This measure provides an estimate of the risk that nitrogen could leave the field through runoff or leaching and reach streams and rivers. “Excess nitrogen,” however, is not synonymous with “nitrogen loss.” A field receiving little excess nitrogen from an agronomic perspective could still lose nitrogen to runoff or leaching.

- The level of program enforcement—that is, the probability that a farmer will be caught and denied program benefits for not complying with the nutrient application standards.

Our results suggest that the majority of MARB farms have low or no excess nitrogen application rates. Only 14.4 percent of farms in the MARB, controlling 25.1 percent of cropland, apply N in excess of crop needs and receive program benefits. These farms contribute 88.1 percent of all excess N applications in the MARB. A hypothetical nutrient-compliance policy could influence these farms.

Under the most recent Farm Act (enacted in 2014), agricultural program benefits subject to compliance provisions included crop insurance premium subsidies, Agricultural Risk Coverage (ARC) payments, Price Loss Coverage (PLC) payments, conservation payments (Environmental Quality Incentive Program, Conservation Stewardship Program, Conservation Reserve Program, and Wetland Reserve Program), marketing loan gains, and disaster payments (table 5.1). Farm-level data on program benefits subject to compliance for most programs were obtained directly from the 2012 Census of Agriculture. The value of crop insurance subsidies to the farmer was estimated as the 2012 county-average per-acre premium subsidy for insured acres (from USDA-Risk Management Agency) multiplied by the farm's insured acres (from the census). ARC and PLC were introduced in the 2014 Farm Act, so data were not available from the 2012 Census of Agriculture. ARC payments were estimated using the 2014 crop- and practice-specific county-level payment rates multiplied by the farm's harvested acres in each eligible crop (from the 2012 Census of Agriculture) multiplied by crop-specific State-level enrollment rates. PLC payments were estimated using crop-specific 2014 payment rates multiplied by the crop-specific output (from census) multiplied by crop-specific State-level enrollment rates. Both the ARC and PLC calculations accounted for the fact that payments are made on 85 percent of base acres.

Table 5.1

Program benefits, farmer compliance costs, and net payments per acre (averages across farms) under hypothetical nutrient compliance policy

	Average excess nitrogen (E) (lbs. per crop acre)					
	0	$0 \leq E < 20$	$0 \leq E < 50$	$0 \leq E < 100$	$100 \leq E$	All farms
	$/crop acre					
Average total program benefits subject to compliance ($/crop acre)	49.0	45.9	49.2	55.1	62.2	49.4
Average compliance cost ($/crop acre)	-	33.4	34.9	36.3	36.9	34.3[a]
Average net compliance benefits ($/crop acre)	-	12.9	14.9	19.8	27.0	15.9[a]

[a] Average for all farms with excess.

Source: USDA, Economic Research Service assessment of USDA program data and Conservation Effects Assessment Project (CEAP) cost data.

Program benefits flow disproportionately to farms in the higher excess categories (see table 5.1). Farms in the highest (nutrient) excess category received 26 percent more benefits than the average farm ($62.20 per acre versus $49.40 per acre).

Nutrient management costs include annualized installation and implementation costs for a Nutrient Management Plan (NMP), and forgone income associated with changes in crop yields net of savings from reduced commercial fertilizer purchases. The per-acre cost of implementing a NMP was estimated at the watershed scale (4-digit Hydrologic Unit Code) with a sample of field-level survey data and field-level modeling results from CEAP (see box, "Conservation Effects Assessment Project," p. 8). CEAP's cost estimates considered the inherent characteristics of the field receiving treatment, so the nutrient management plan and associated costs were tailored to each sample site. Installation and implementation costs include materials, equipment, labor, operations, maintenance, and technical assistance. Costs for nutrient management planning were assumed to be 20 percent higher if the field received animal manure. Estimated yield changes from adopting NMP were obtained from CEAP for each crop in the rotation reported for the survey field and valued with 2012 price data from NASS. The value of yield changes was then averaged over the rotation. Similarly, fertilizer cost savings were estimated with the CEAP data for each crop in the rotation and averaged over the rotation.

Program benefits are estimated to exceed compliance costs in all excess categories. Compliance costs average $34.30 per acre and do not vary much across "excess nitrogen" categories. Average net benefits for all farms with excess nutrients are $15.89 per acre and range from $12.90 to $27 per acre, with net benefits increasing across excess application ranges (table 5.1). This suggests that compliance would provide a strong incentive for farms with the greatest excess nitrogen applications to adopt nutrient management plans.

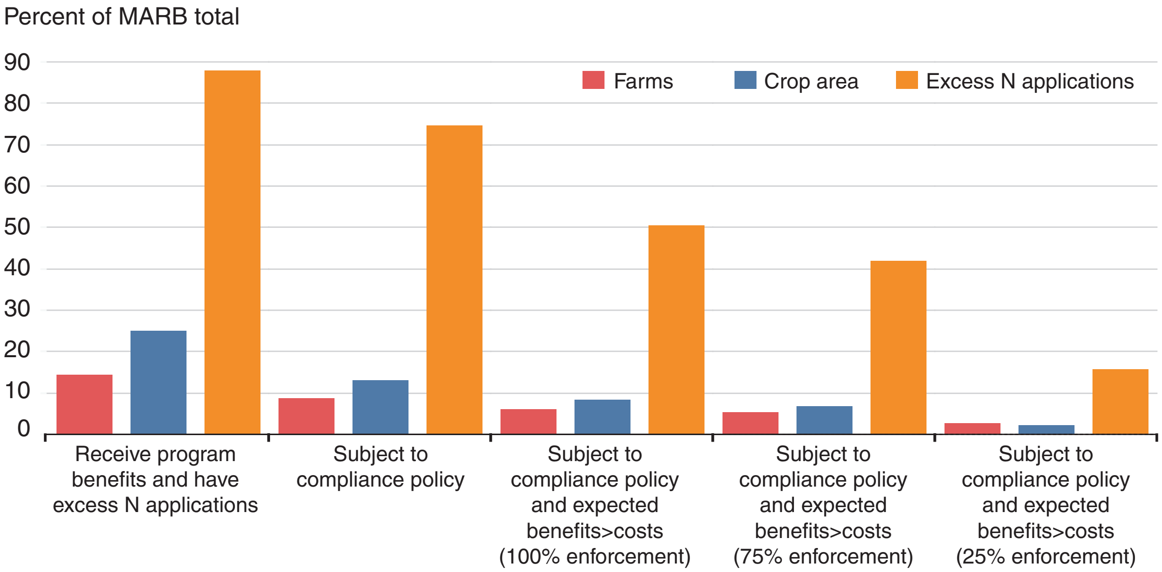
The expected cost of nutrient compliance is influenced by the expectation of being found out of compliance through inspection. To illustrate the relationship between enforcement and policy effectiveness, we consider three values for the probability of being caught for noncompliance: 100, 75, and 25 percent. Details of the probabilistic model framework used in our analysis can be found in Ribaudo et al. (2017).

Assuming a compliance policy that disallows excess application of nutrients above 40 percent of crop needs (mirroring the practice standard for nutrient management described in the box, "Conservation Systems for Reducing Nutrients") and assuming 100-percent enforcement, our analysis suggests 8.7 percent of MARB farms would be affected by compliance, and 71 percent of those—6.2 percent of total MARB farms—would have an incentive to comply (because program benefits exceed nutrient management costs) (figure 5.1). Nutrient management plans would be implemented on cropland receiving over half (50.6 percent) of all excess nutrient applications. With an enforcement rate of 25 percent, the share of farms that is estimated to comply falls to 31 percent of those affected by compliance, or 2.7 percent of all farms in the MARB, and the share of excess nutrients that would be controlled falls to 15.7 percent. (Given the excess application allowances noted above, implementing nutrient management would not reduce excess applications to 0.)

How much nutrient load reduction to the Gulf could a nitrogen-compliance policy generate? To explore this question, we return to the REAP model. Assuming 100-percent enforcement, implementing a nutrient management practice on 8.4 percent of cropland (20 million acres) in REAP model regions with high concentrations of cropland subject to compliance would result in an estimated 2.1-percent reduction in N loadings and a 1.9-percent reduction in phosphorus (P) loadings to the Gulf.

Figure 5.1

Policy scope and effectiveness of nitrogen compliance under alternative enforcement levels in the Mississippi/Atchafalaya River Basin



Note: A farm is subject to compliance if it receives Government payments and it exceeds an excess nitrogen rate of 40 percent. Benefits>costs means that compliance program benefits (program payments and benefits from crop insurance) exceed compliance costs (costs of adopting required nutrient management practices).
Enforcement level indicates the probability that a farmer would be caught and denied program benefits for not complying with the nutrient standards. N = nitrogen.
Source: USDA, Economic Research Service calculations using 2012 Census of Agriculture data.

The relatively small impacts in the Gulf arise in part because over 66 percent of crop acres with high excess nitrogen applications that are likely to adopt nutrient management in this scenario are in the Missouri and Arkansas-White-Red sub-basins, regions that contribute little nutrient load to the Gulf due to low delivery ratios. Only 7 percent of MARB acres likely to adopt nutrient management are in the Lower Mississippi, where a majority of nutrient reductions under the cost-effective Gulf Constraints scenario occur.

Another reason for the small remediation impact on Gulf nutrients is the nature of the compliance program design in the REAP analysis. We targeted for the establishment of nutrient management programs those *regions* identified by the farm-based analysis as having a large number of farms with excess nitrogen application. However, the REAP analysis then simulates an acreage-based program design, where an acreage objective for BMP enrollment in those regions is established and met. The acres placed under nutrient management are those that will have minimum impact on the economic surplus associated with production, which are not necessarily those with the highest nitrogen losses and the most significant nitrogen reduction gains from improved nutrient management. As indicated in the farm-based analysis, a significant portion of farms, and cropland acreage, have low or no excess nitrogen application rates, so the nitrogen benefits arising from adoption of improved nutrient management on that land may be small, even at the local level.

While compliance programs may provide an incentive for all cropland receiving program benefits to adopt nutrient management, such a policy may not be cost-effective from a Gulf standpoint, based on where within the MARB those nutrient management plans would be most effective at reducing excess nitrogen. Furthermore, a failure to target farms that have high potential for nitrogen loss reduction may impose nutrient management costs on farms that have low nutrient benefits associated with additional reduction efforts. On the other hand, such farms may already be in compliance or may be able to comply at little cost; our analysis was unable to explore the question at that level of detail.

Nutrient subsidy (Pay for performance)

All USDA financial assistance for conservation practices is currently based on practice costs. An alternative approach, known as pay-for-performance, is to base the level of financial assistance on the amount of environmental service produced. A subsidy payment based on the amount of nutrient reduction would encourage most producers to examine their nutrient management practices and determine the financial benefit from reducing nutrient losses (Ribaudo et al., 1999; Shortle et al., 2012; Ribaudo et al., 2014). Unlike traditional cost-share payments, pay-for-performance is not limited to a share of costs, so a producer might increase net returns if nutrient abatement costs are less than payment rates. Farmers can also choose practices to reduce nutrient loss, like changing crop rotations, that generate nutrient reductions without traditional cost-sharing. This flexibility in approach leads to more cost-effective solutions to nutrient management (Ribaudo et al., 1999). Appropriate subsidies on N and P reductions could incentivize the management and land-use changes necessary to achieve the Gulf hypoxia goals.

In this analysis, the subsidy rates for achieving 45-percent reductions in N and P delivered to the Gulf are an estimated \$5.84 per pound for N and \$13.50 per pound for P.[10] Equivalent subsidy rates on regional discharge can be calculated using the appropriate nutrient delivery ratios. Total payments for nutrient reductions in the MARB would be over \$4.9 billion annually to achieve the cost-effective configuration of nutrient reduction and cropping practices estimated under the Gulf Constraints scenario, a cost borne by taxpayers. Farmers would be compensated for their changes in management, so net returns—inclusive of subsidy payments—would not decline.

While a pay-for-performance policy based on such subsidies would incentivize producer behavior leading to nutrient load reductions, the cost to taxpayers can be significant. Such direct costs may be outweighed by the more dispersed benefits associated with increasing water quality within the MARB and shrinking the extent of the hypoxic area in the Gulf, but placing a value on such benefits is beyond the scope of this study. Furthermore, there are a number of design and technical challenges associated with establishing pay-for-performance programs. Basing payments on nutrient reductions would require a precise tool or methodology for estimating the amount of nutrient reduction a field could produce under different management systems. Program design challenges include how and whether to compensate "good actors" for nutrient-reduction efforts they are already engaged in, and how to avoid incentive structures that encourage existing adopters to drop current conservation practices in order to re-adopt them and qualify for subsidies. The potential for such perverse incentives could increase the cost of a pay-for-performance program significantly.

Another complaint about such subsidy schemes concerns the appropriateness of "stacking" payments for nutrient reductions (i.e., paying for both nutrients separately) when the conservation practices adopted in response to those payments reduce both nutrients simultaneously. In other

---

[10] Subsidy rates are the shadow prices for the REAP constraints on nitrogen and phosphorus loadings to the Gulf. In simpler terms, it is the benefit of relaxing the constraint by 1 pound of nutrient.

words, if the subsidization of practices that reduce N loss also reduces the loss of P from fields, why should we also pay for the resulting reduction of P? Controlling both nitrogen and phosphorus flows from agriculture to the Gulf is necessary because they both affect eutrophication, but to what extent are these objectives complementary, in that controlling for one also controls for the other?

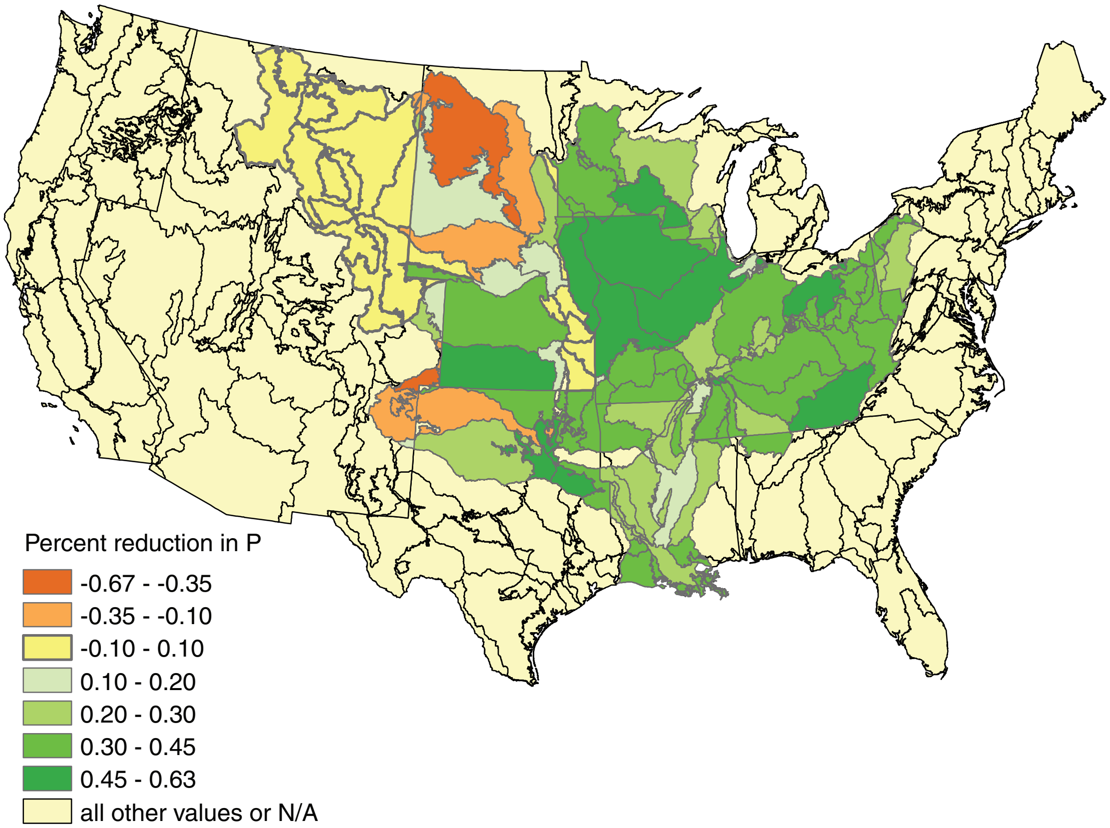
To explore this question, we ran the Gulf and Regional Constraints scenarios controlling for the two nutrients separately. For the Gulf Constraints scenario, when only N is constrained, the optimal distribution of practices to achieve the 45-percent reduction in N also achieves a 37-percent reduction in P deliveries to the Gulf, indicating a fairly high degree of complementarity between reductions in N and P. When only N is subsidized, however, a higher subsidy rate on N is required than when both N and P are subsidized; the subsidy rate on N necessary to arrive at a 45-percent reduction in N increases by 26 percent—up to $7.34/lb. The total cost of achieving the N reduction when only N is subsidized—$5.1 billion—therefore actually exceeds the cost of a subsidy program with joint payments that reduces both nutrients by 45 percent.

Conversely, if only phosphorus arrivals at the Gulf are constrained, those reductions are accompanied by a 25.9-percent reduction in nitrogen, and the required subsidy rate to achieve a 45-percent reduction in phosphorus arrivals at the Gulf increases to $51.98/lb. The program—with a cost of $3.3 billion—achieves the 45-percent phosphorus-reduction goal but falls well short of the objective for a 45-percent reduction in N loadings to the Gulf. These results are consistent with the findings of Rabotyagov et al. (2010), who also find that controlling separately for N loadings is more effective at reducing P than controlling separately for P is at reducing N.

The degree to which reductions in one nutrient produce changes in the other nutrient varies regionally. Constraining the nutrients separately under the Regional Constraints scenario highlights the regional variability in complementarity between N and P discharge reductions. Controlling only for N discharges at the regional level produces a 33.8-percent reduction in phosphorus delivery to at the Gulf. However, the proportional declines in P are not evenly distributed across the landscape. Controlling for N is ineffective at also controlling for P in the Missouri and parts of the Arkansas-White-Red sub-basins (figure 5.2). In contrast, in some production regions within the Upper Mississippi and Tennessee sub-basins, achieving a 45-percent reduction in N discharges results in a reduction in P discharges of more than 45 percent. Given the many adjustments in moving from the dual-constraint case to the single-constraint case, there are many possible drivers for such results. Further research, with a more systematic set of sensitivity analyses varying isolated variables, would help clarify the offsetting drivers contributing to nutrient-reduction complementarities.

Figure 5.2

The percent reduction in phosphorus (P) discharge when nitrogen discharges at watershed outlets are reduced by 45 percent



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service analysis with REAP-CEAP framework.

Chapter 6: Summary: Policy Lessons for Reducing Agricultural Nutrients to the Gulf of Mexico

This report provides some insights into how policies for addressing Gulf hypoxia and other nutrient-related water quality issues in the Mississippi/Atchafalaya River Basin (MARB) could be made more cost-effective. How nutrient-reduction policy goals are structured—whether on a broader watershed scale or on a more localized regional basis—can determine the most cost-effective location and mix of conservation investments. Also, actions taken within the basin could have implications for water quality protection efforts and farm economics outside the basin.

A mix of conservation practices is needed to meet hypoxia goals

A wide range of changes in crop production practices in the MARB would be needed to cost-effectively meet nutrient-reduction targets, a consequence of the region's large area and the wide range of climate, hydrology, and agricultural production systems. No single practice alone can achieve the goals. At the intensive margin, nutrient discharge per acre of cropland is reduced by shifting crop rotations, adopting nutrient-reducing conservation systems, and altering tillage and other on-field cropping practices. At the extensive margin, some marginal cropland is removed from production. Buffers and wetlands operate at both the intensive and extensive margins, intercepting nutrients discharged from the field while reducing available land in crop production. Relative reliance on on-field practices, off-field practices, and cropland idling varies across regions, depending on how nutrient-reduction constraints are structured.

Location is key in cost-effective control of nutrients reaching the Gulf

If the only goal is cost-effectively reducing the size of the hypoxic zone in the Gulf of Mexico, proximity to the Gulf largely determines where the most cost-effective nutrient management occurs. Even though more than half of the nitrogen and phosphorus that reaches the Gulf comes from the Ohio and Upper Mississippi sub-basins, the least-cost control imperative dictates that the largest share of load reductions comes from the Lower Mississippi. High delivery ratios and nutrient loss rates make nutrient reductions here more cost effective than further upstream. More productive cropland in the Ohio and Upper Mississippi sub-basins, and high costs of management changes, are also factors determining the relative costs of abatement. In contrast, the Missouri sub-basin—characterized by low delivery ratios and low nitrogen losses per acre of cropland—is estimated to see very little nutrient-reduction effort.

In the pursuit of the Gulf hypoxia objectives, there are therefore tradeoffs identified between cost-effectiveness and the equitable distribution of impacts to farmers. When reductions are allocated purely based on cost-effectiveness and without regard to where the nutrients originate, farmers in the Lower Mississippi would bear a disproportionate share of responsibility for reducing nutrient loads to the Gulf. On the other hand, basing a nutrient policy solely on a sub-basin's baseline share of contributed nutrients to the Gulf would spread conservation efforts more widely across the MARB but lead to a higher cost for achieving the same reduction goal.

Limiting conservation objectives to Gulf water quality reduces the necessary scale of conservation effort on working lands

Under the ***Gulf Constraints*** scenario, reducing nutrient loads to the Gulf entails maintenance of current conservation practices and implementation of onsite and off-site nutrient-management measures on an additional 36.8 million acres of working cropland (15.4 of baseline acreage), strategically located across the MARB. Any other configuration of the management systems explored in this analysis, in terms of which practices are applied and where, will require more crop acreage to be treated and/or greater cost to achieve the same amount of reduction in nutrient loads to the Gulf. To the extent that demands for Federal financial/technical assistance scale up with implementation of conservation practices on working lands, focusing conservation efforts on those acres with the greatest nutrient abatement cost-efficiency can reduce financial and technical resources required for nutrient abatement.

In contrast, achieving the same Gulf hypoxia objective by curtailing nutrient impairments more broadly across production regions (the ***Regional Constraints*** scenario) expands the scale of nutrient-reduction practices on working lands by an additional 41.8 million acres and pushes conservation effort into regions, such as the Missouri and Arkansas-White-Red sub-basins, that may have fewer remaining opportunities for low-cost nutrient-reductions. The increased cost associated with that expansion would likely entail greater demands on Federal financial and technical assistance. However, water quality benefits would be more widely dispersed throughout the MARB, and local water quality benefits may be expected to be greater as more nutrients are prevented from entering surface waters overall.

Market effects transfer some of the nutrient-reduction impacts to other sectors and regions

Our analysis is also able to estimate how the extensive implementation of conservation systems for reducing nutrient discharges to water resources affects crop production and commodity prices nationally. The scale of production adjustments required to achieve a 45-percent decline in nutrient loadings across the MARB is likely to affect commodity markets and shift some costs to purchasers of agricultural products. Higher estimated crop prices mitigate the costs that producers bear for implementing conservation systems (one reason why our estimated economic impact to producers is lower than those of previous studies).

Summing up only implementation costs for cropland undergoing change while ignoring price effects would likely overestimate costs to the crop sector. Higher commodity prices caused by efforts to reduce Gulf hypoxia could increase the intensity of production and expand cropland area outside the MARB. Both of these outcomes result in increased nutrient and sediment loss in watersheds outside the MARB. While not large, estimated increases in nutrient and sediment loss beyond the MARB would be of concern for other regions dealing with water quality impairments.

Conservation programs can contribute to the cost-effective control of nutrient losses in the MARB

Given the data and assumptions in our model, we identified a distribution of conservation efforts across the MARB that would reduce nutrient loadings to the Gulf by 45 percent at least cost to producers and consumers. Conservation programs could induce farmers in the most hydrologically connected sub-watersheds to adopt the most cost-effective nutrient-reduction practices.

Targeting program assistance to sub-basins such as the Lower Mississippi that can produce large reductions in delivered nutrients at low cost might help in allocating the cost of the conservation effort most efficiently.

Wetland restoration tended to be more cost effective than the other nutrient abatement practices, followed by drainage water management and nutrient management. Emphasizing such practices through extension or in the contract selection process could raise program cost-effectiveness. However, no single practice is sufficient to achieve the full 45-percent reduction in Gulf nutrient loading, and the cost-effectiveness of most practices varies widely across regions. We assume homogeneity of production and impact within the REAP production regions; given the heterogeneity that actually exists within those regions—in soils, topography, proximity to waterways, etc.—more refined analyses are critical for identifying the relative cost-effectiveness of practices at a more local scale.

Policy approaches for achieving a cost-effective nutrient reduction in the MARB are complicated by the wide variability in cost-effectiveness across both regions and practices. Efforts to cost-effectively target conservation funds must consider both regions and practices, and targets may vary depending on whether conservation objectives are Gulf-only or are more broadly applied to address local water quality concerns MARB-wide as well. Furthermore, targeting is only effective if those farmers who can provide the most cost-effective nutrient reductions agree to adopt the most effective practices. The proactive development of relationships by resource managers with those farms in a watershed most in need of improvement, the facilitation of peer learning networks among producers, and the provision of appropriate education, technical, and financial assistance for the most cost-effective practices could improve the efficiency of a voluntary approach (Shortle et al., 2012; McGuire et al., 2013; Ribaudo, 2017).

A pay-for-performance approach that bases conservation payment rates on the amount of nutrient reduction achieved (either at the Gulf or within more localized production regions, depending on water quality goals) could provide the greatest financial incentive to those farmers who can reduce nutrient losses most cost-effectively. Such an approach precludes the need to target regions or practices, and in theory would produce the most cost-effective allocation of nutrient control. This approach would require some way of estimating field-level nutrient losses; modeling tools to do this are becoming more readily available. It also may be possible in designing a pay-for-performance program to harness the complementarity of nitrogen and phosphorus reductions, with subsidies offered for only one nutrient or the other. Our findings suggest, however, that complementarity is asymmetric across the nutrients and that its strength varies widely by region. More refined modeling is needed to characterize those situations in which payment stacking can be bypassed without undercutting nutrient-reduction objectives.

Other programs relying on voluntary participation may hold promise for tackling the nutrient-reduction issue in the MARB. We demonstrate that a nutrient-compliance policy tied to farm program benefits could provide an economic incentive for farmers with high excess nutrient applications to voluntarily seek assistance for developing and implementing nutrient management plans. Such a policy does tend to impact application rates on farms with the highest excess nutrient applications, but the analysis suggests that even a more comprehensive nutrient management plan is not, when applied in isolation, sufficient to achieve the goals for reduction of nutrient loadings. A larger and more diverse set of onfield and off-field conservation strategies will be necessary to ensure achievement of the Gulf hypoxia goals.

References

Batie, S. 2010. "Taking Conservation Seriously as a Wicked Problem," in P. Nowak and M. Schnepf (eds.), *Managing Agricultural Landscapes for Environmental Quality II: Achieving More Effective Conservation*, Soil and Water Conservation Society of America, Ankeny, IA, pp. 143-156.

Baustian, M.M., and N. Rabalais. 2009. "Seasonal Composition of Benthic Macroinfauna Exposed to Hypoxia in the Northern Gulf of Mexico," *Estuaries and Coasts* 32:975-983.

Baustian, M.M., J.K. Craig, and N.N. Rabalais. 2009. "Effects of summer 2003 hypoxia on macrobenthos and Atlantic croaker foraging selectivity in the northern Gulf of Mexico," *Journal of Experimental Marine Biology and Ecology* 381: S31-S37.

Bouwman, A.F., M.F.P. Bierkens, J. Griffioen, M.M. Hefting, J.J. Middelburg, H. Middelkoop, and C.P. Slomp. 2013. "Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: towards integration of ecological and biogeochemical models," *Biogeosciences*. Jan. Vol.10, 1-23.

Chesapeake Bay Program. 2016. *Wetlands and Wetland Restoration – Recommendations of the Wetland Expert Panel for the incorporation of non-tidal wetland best management practices (BMPs) and land uses in the Phase 6 Chesapeake Bay Watershed Model*. Annapolis, MD. December.

Christianson, L., J. Tyndall, and M. Helmers. 2013. "Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage," *Water Resources and Economics* 2-3:30-56.

Claassen, R., M. Bowman, V. Breneman, T. Wade, R. Williams, J.R. Fooks, L. Hansen, R. Iovanna, and C. Loesch. 2017. *Conservation Compliance: How Farmer Incentives Are Changing in the Crop Insurance Era*, ERR-234, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Claassen, R., V. Breneman, S. Bucholtz, A. Cattaneo, R. Johansson, and M. Morehart. 2004. *Environmental Compliance in U.S. Agricultural Policy: Past Performance and Future Potential*, AER-832, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Craig, J.K. 2012. "Aggregation on the edge: Effects of hypoxia avoidance on the spatial distribution of brown shrimp and demersal fishes in the northern Gulf of Mexico," *Marine Ecological Progress Series* 445:75-95.

Craig, J.K., and S.H. Bosman. 2012. "Small spatial scale variation in fish assemblage structure in the vicinity of the northwestern Gulf of Mexico hypoxic zone," *Estuaries and Coasts* 36(2):268-285.

Craig, J.K., L.B. Crowder, and T.A. Henwood. 2005. "Spatial distribution of brown shrimp (*Farfantepenaeus aztecus*) on the northwestern Gulf of Mexico shelf: Effects of abundance and hypoxia," *Canadian Journal of Fisheries and Aquatic Science* 62:1295-1308.

Crumpton, W.G., G.S. Stenback, B.A. Miller, and M. J. Helmers. 2006. “Potential benefits of wetland filters for tile drainage systems: impact on nitrate loads to Mississippi River subbasins.” Final Project Report to U.S. Department of Agriculture Project Number IOW06682.

Diaz, R.J., and R. Rosenberg. 2008. “Spreading dead zones and consequences for marine ecosystems,” *Science* 321:926-929.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. “Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile-Drained Midwestern Soils,” *Agronomy Journal* 94:153-171.

Dodd, R.J., and A.N Sharpley. 2016. “Conservation practice effectiveness and adoption: unintended consequences and implications for sustainable phosphorus management,” *Nutrient Cycling in Agroecosystems* 104(3):373-392.

Doering, O.C., F. Diaz-Hermelo, C. Howard, R. Heimlich, F. Hitzhusen, R. Kazmierczak, J. Le, L. Libby, W. Milon, T. Prato, and M. Ribaudo. 1999. *Evaluation of the Economic Costs and Benefits of Methods for Reducing Nutrient Loads to the Gulf of Mexico: Topic 6 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico*, Decision Analysis Series No. 20, NOAA Coastal Ocean Program, U.S. Department of Commerce, Silver Spring, MD.

Fennessy, M.S., C.C. Brueske, and W.J. Mitsch. 1994. “Sediment deposition patterns in restored freshwater wetlands using sediment traps,” *Ecological Engineering* 3: 409–428.

Fink, D.F., and W.J. Mitsch. 2004. “Seasonal and storm event nutrient removal by a created wetland in an agricultural watershed,” *Ecological Engineering* 23:313–325.

Fox, R.H., W.P. Piekielek, and K.E. Macneal. 1996. “Estimating Ammonia Volatilization Losses From Urea Fertilizers Using a Simplified Micrometerological Sampler,” *Soil Science Society of America Journal* 60:596-601.

Freney, J.R., J.R. Simpson, and O.T. Denmead. 1981. “Ammonia Volatilization,” *Ecological Bulletin* 33:291-302.

Gassman, P.W., J.R. Williams, S. Wang, A. Saleh, E. Osei, L. Hauck, C. Izaurralde, and J. Flowers. 2009. *The Agricultural Policy Environmental Extender (APEX) model: An emerging tool for landscape and watershed environmental analyses*, Technical Report 09-TR 49, CARD, Iowa State University, Ames, IA.

Hutchinson, G.L., A.R. Mosier, and C.E. Andre. 1982. “Ammonia and Amine Emissions From a Large Cattle Feedlot,” *Journal of Environmental Quality* 11:288-293.

Johansson, R., M. Peters, and R. House. 2007. *Regional Environment and Agriculture Programming Model (REAP)*, TB-1916, U.S. Department of Agriculture, Economic Research Service.

Kadlec, R. H., and D. L. Hey. 1994. “Constructed wetlands for river water quality improvement,” *Water Science and Technology* 29:159-168.

Kleinman, P.J.A., A.N.Sharpley, R.W. McDowell, D.N. Flaten, A.R. Buda, L. Tao, L. Bergstrom, and Q. Zhu. 2011. "Managing agricultural phosphorus for water quality protection: principles for progress," *Plant Soil* 349(1-2):169-182.

Kovacic, D., R.M. Twait, M.P. Wallace, and J.M. Bowling. 2006. "Use of created wetlands to improve water quality in the Midwest-lake Bloomington case study," *Ecological Economics* 28:258-270.

Louisiana Universities Marine Consortium (LUMCON). 2017. "Hypoxia in the Northern Gulf of Mexico," Press release, August 2, 2017.

Malcolm, S., E. Marshall, M. Aillery, P. Heisey, M. Livingston, and K.D. Rubenstein. 2012. *Agricultural Adaptation to a Changing Climate: Economic and Environmental Implications Vary by U.S. Region*, ERR-136, U.S. Department of Agriculture, Economic Research Service.

Marshall, E.M., M. Caswell, S. Malcolm, M. Motamed, J. Hrubovcak, C. Jones, and C. Nickerson. 2011. *Measuring the Indirect Land-Use Change Associated with Increased Biofuel Feedstock Production: A Review of Modeling Efforts: Report to Congress,* AP-054, U.S. Department of Agriculture, Economic Research Service.

Marshall, E.M., M. Aillery, S. Malcolm, and R. Williams. 2015. *Climate Change, Water Scarcity, and Adaptation in the U.S. Fieldcrop Sector,* ERR-201, U.S. Department of Agriculture, Economic Research Service.

Mayer, P.M., S. Reynolds, T. Canfield, and M. McCutchen. 2005. *Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations*, EPA/600/R-05/118. U.S. Environmental Protection Agency, Washington, DC.

McGuire, J., L.W. Morton, and A.D. Cast. 2013. "Reconstructing the Good Farmer Identity: Shifts in Farmer Identities and Farm Management Practices to Improve Water Quality." *Agriculture and Human Values* 30:57-69.

McLellan, E., D. Robertson, K. Schilling, M. Tomer, J. Kostel, D. Smith, and K. King. 2015. "Reducing Nitrogen Export from the Corn Belt to the Gulf of Mexico: Agricultural strategies for Remediating Hypoxia," *Journal of the American Water Resources Association* 51(1):263-289.

Mississippi River Gulf of Mexico Watershed Nutrient Task Force. 2008. *Gulf Hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin*, U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC.

Mitsch, W.J., J.W. Day, L. Zhang, and R. R. Lane. 2005. "Nitrate-nitrogen retention in wetlands in the Mississippi River Basin," *Ecological Engineering* 25:267-278.

Mosier, A.R., and L. Klemedtsson. 1994. "Measuring Denitrification in the Field," in R.W. Weaver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai, and A. Wollum (eds.), *Methods of Soil Analysis: Part 2, Microbiological and Biochemical Properties*, Soil Science Society of America, pp. 1047-1065.

Novotny, V., and H. Olem. 1994. *Water Quality: Prevention, Identification, and Management of Diffuse Pollution.* New York: Van Nostrand Reinhold.

Nowak, P., S. Bowen, and P.E. Cabot. 2006. "Disproportionality as a Framework for Linking Social and Biophysical Systems," *Sociology of Natural Resources* 19(2):153-173.

Peoples, M.B., J.R. Freney, and A.R. Mosier. 1995. "Minimizing Gaseous Losses of Nitrogen," in P.E. Bacon (ed.), *Nitrogen Fertilization in the Environment*, New York: Marcel Dekker, Inc., pp. 565-602.

Petrolia, D.R., and P.H. Gowda. 2006. "An Analysis of the Role of Tile-Drained Farmland Under Alternative Nitrogen Abatement Policies," *Journal of Agricultural and Resource Economics* 31(3):580-594.

Phipps, R.G., and W.G. Crumpton. 1994. "Factors affecting nitrogen loss in experimental wetlands with different hydrologic loads," *Ecological Engineering* 3:399-408.

Preston, Stephen D., Richard B. Alexander, Gregory E. Schwarz, and Charles G. Crawford. 2011. "Factors Affecting Stream Nutrient Loads: A Synthesis of Regional SPARROW Model Results for the Continental United States," *Journal of the American Water Resources Association*. Oct. Vol.47(5): 891-915.

Rabalais, N.N., and R.E. Turner, eds. 2001. *Coastal Hypoxia: Consequences for Living Resources and Ecosystems*, Coastal and Estuarine Studies 58, Washington, DC: American Geophysical Union.

Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang. 2010. "Dynamics and distribution of natural and human-caused hypoxia," *Biogeosciences* 7:585-619.

Rabalais, N.N., R.E. Turner, and W.J. Wiseman. 2002. "Gulf of Mexico Hypoxia, a.k.a. "The Dead Zone," *Annual Review of Ecology and Systematics* 33:235-263.

Rabotyagov, S., T. Campbell, M. Jha, P.W. Gassman, J. Arnold, L. Kurkalova, S. Secchi, H. Feng, and C.L. Kling. 2010. "Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone," *Ecological Applications* 20(6):1542-1555.

Rabotyagov, S.S., C.L. Kling, P.W. Gassman, N.N. Rabalais, and R.E. Turner. 2014a. "The Economics of Dead Zones: Causes, Impacts, Policy Challenges, and Model of the Gulf of Mexico Hypoxic Zone," *Review of Environmental Economics and Policy* 8(1):58-79.

Rabotyagov, S.S., T.D. Campbell, M. White, J.G. Arnold, J. Atwood, M.L. Norfleet, C.L. Kling, P.W. Gassman, A. Valcu, J. Richardson, R.E. Turner, and N.N. Rabalais. 2014b. "Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone." *Proceedings of the National Academy of Sciences* 111(52): 18530-18535, December.

Randall, G.W., J.A. Delgado, and J.S. Schepers. 2008. "Nitrogen Management To Protect Water Resources," in J.S. Schepers, W.R. Raun, R.F. Follett, R.H. Fox, and G.W. Randall (eds.), *Nitrogen in Agricultural Systems,* Agronomy Monograph 49, Soil Science Society of America, pp. 911-946.

Randall, G.W., M.J. Goss, and N.R. Fausey. 2010. "Nitrogen and Drainage Management To Reduce Nitrate Losses to Subsurface Drainage," in J.A. Delgado, and R.F. Follett (eds.), *Advances in Nitrogen Management for Water Quality*, Soil and Water Conservation Society.

Ribaudo, M. 2017. "Conservation Programs Can Accomplish More with Less by Improving Cost-Effectiveness," *Choices* 32(4):1-6.

Ribaudo, M.O., R.D. Horan, and M.E. Smith. 1999. *Economics of Water Quality Protection from Non-point Sources: Theory and Practice*, AER-782, U.S. Department of Agriculture, Economic Research Service.

Ribaudo, M., N. Key, and S. Sneeringer. 2017. "The Potential Role for a Nitrogen Compliance Policy in Mitigating Gulf Hypoxia," *Applied Economic Perspectives and Policy* 39(3):458-478.

Ribaudo, M., J. Savage, and M. Aillery. 2014. *An Economic Assessment of Policy Options To Reduce Agricultural Pollutants in the Chesapeake Bay*, ERR-166, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Robertson, D.M., G.E. Schwarz, D.A. Saad, and R.B. Alexander. 2009. "Incorporating uncertainty into the ranking of SPARROW model nutrient yields from Mississippi/Atchafalaya River Basin watersheds," *Journal of the American Water Resources Association* 45(2):534-549.

Robertson, D.M., D.A. Saad, and G.E. Schwarz. 2014. "Spatial Variability in Nutrient Transport by HUC8, State, and Subbasin Based on Mississippi/Atchafalaya River Basin SPARROW Models," *Journal of American Water Resources Association* 50(4):988-1009.

Robertson, D.M., and D.A. Saad. 2013, "SPARROW Models Used to Understand Nutrient Sources in the Mississippi/Atchafalaya River Basin," *Journal of Environmental Quality* 42(5):1422-1440.

Sands, R.D., S.A. Malcolm, S.A. Suttles, and E. Marshall. 2017. *Dedicated Energy Crops and Competition for Agricultural Land*. ERR-223, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Sharpe, R.R., and L.A. Harper. 1995. "Soil, Plant, and Atmospheric Conditions as They Relate to Ammonia Volatilization," *Fertilizer Research* 42:149-153.

Sharpley, A.N., P.J.A. Kleinman, R.W. McDowell, M. Gitau, and R.B. Bryant. 2002. "Modeling phosphorus transport in agricultural watersheds: Processes and possibilities," *Journal of Soil and Water Conservation* 57(6):425-439.

Shortle, J., M. Ribaudo, R. Horan, and D. Blandford. 2012. "Reforming Agricultural Nonpoint Pollution Policy in an Increasingly Budget-Constrained Environment," *Environmental Science and Technology* 46(3):1316-1325.

Smith, M.D., F. Asche, L.S. Bennear, and A. Oglend. 2014. "Spatial-dynamics of Hypoxia and Fisheries: The Case of Gulf of Mexico Brown Shrimp," *Marine Resource Economics* 29(2):111-131.

Smith, M.D., A. Oglend, A.J. Kirkpatrick, F. Asche, L.S. Bennear, J.K. Craig, and J.M. Nance. 2017. "Seafood prices reveal impacts of a major ecological disturbance," *Proceedings of the National Academy of Sciences.* January. DOI: 10.1073/pnas.1617948114

Sprague, L.A., and J.A.M. Gronberg. 2012. "Relating Management Practices and Nutrient Export in Agricultural Watersheds of the United States," Journal of Environmental Quality 41: 1939-1950.

Tomer, M.D., S.A. Porter, K.M.B. Boomer, D.E. James, J.A. Kostel, M.J. Helmers, T.M. Isenhart, and E. McLellan. 2015. "Agricultural Conservation Planning Framework: 1. Developing Multipractice Watershed Planning Scenarios and Assessing Nutrient Reduction Potential," *Journal of Environmental Quality* 44:754-767.

Turner, R.E., and N.N. Rabalais. 2003. "Linking Landscape and Water Quality in the Mississippi River Basin for 200 Years," *BioScience* Vol. 53 No. 6, pp. 563-572.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA, NASS). 2014. *USDA Census of Agriculture, 2012*. Special tabulation of conservation practice data (unpublished). Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). 2011. *Assessment of the effects of conservation practices on cultivated cropland in the Ohio-Tennessee River basin.* Conservation Effects Assessment Project. Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). 2012a. *Assessment of the effects of conservation practices on cultivated cropland in the Missouri River basin*. Conservation Effects Assessment Project. Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). 2012b. *Assessment of the effects of conservation practices on cultivated cropland in the Upper Mississippi River basin*. Conservation Effects Assessment Project. Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). 2013a. *Assessment of the effects of conservation practices on cultivated cropland in the Arkansas-White-Red River basin*. Conservation Effects Assessment Project. Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). 2013b. *Assessment of the effects of conservation practices on cultivated cropland in the Lower Mississippi River basin*. Washington, DC.

U.S. Environmental Protection Agency (U.S. EPA). 2017. *Mississippi River/Gulf of Mexico Watershed Nutrient Task Force: 2017 Report to Congress.* Washington, DC.

U.S. Environmental Protection Agency, 2011. *Nitrogen and Phosphorus Pollution in the Mississippi River Basin: Findings of the Wadeable Streams Assessment*. EPA 841-F-11-004. Washington, DC.

U.S. Environmental Protection Agency Science Advisory Board (U.S. EPA, SAB). 2008. *Hypoxia in the Northern Gulf of Mexico*. Washington, DC.

White, M.J., C. Santhi, N. Kannan, J.G. Arnold, D. Harmel, L. Norfleet, P. Allen, M. DiLuzio, X. Wang, J. Atwood, E. Haney, and M. Vaughn Johnson. 2014. "Nutrient delivery from the Mississippi River to the Gulf of Mexico and effects of cropland conservation," *Journal of Soil and Water Conservation* 69(1):26-40.

Williams, J.R., R.C. Izaurralde, and E.M. Steglich. 2008. *Agricultural Policy/Environmental eXtender Model: Theoretical documentation version 0604*, BREC Report # 2008-17. Temple, TX: Texas AgriLIFE Research, Texas A&M University, Blackland Research and Extension Center.

Wu, J., R.M. Adams, C.L. Kling, and K. Tanaka. 2004. "From microlevel decisions to landscape changes: An assessment of agricultural conservation policies," *American Journal of Agricultural Economics* 86(1):26-41.

Xue, Y., D. A. Kovacic, M. B. David, L. E. Gentry, R. L. Mulvaney, C. W. Lindau. 1999. "In situ measurements of denitrification in constructed wetlands,"*Journal of Environmental Quality* 28:263–269.

Appendix 1: The Regional Environment and Agriculture Programming (REAP) Model

The agronomic and economic impacts of the scenarios are estimated with the Regional Environment and Agriculture Programming (REAP) model, a mathematical optimization model that quantifies agricultural production and its associated environmental impacts for 273 production regions across the United States (Johansson, Peters, and House, 2007). The model uses as input data the technological coefficients on production activities, levels of fixed resources, demand relationships for final products, and costs of production and purchased inputs, and generates a solution that gives the equilibrium prices and quantities of final goods, the pattern of use of the factors of production, regional patterns of commodity production, and imputed prices for owned resources and production activities.

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—to maximize the economic surplus resulting from that production (consumer and producer surpluses). 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. Performance indicators include regional values for land use, input use, crop and animal production and prices, and environmental emissions such as erosion and nutrient loadings. REAP has been used to evaluate a number of resource issues, including adaptation to climate change (Marshall et al., 2015; Malcolm et al., 2012) and biofuels growth (Marshall et al., 2011; Sands et al., 2017).

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. 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 acreage distribution constraints that are parameterized to reflect historically observed patterns of production.

Livestock production (swine, dairy, poultry, and cattle) in the model responds to changes in feedgrain prices, but REAP does not currently include manure production in a way that is useful for this analysis, so a link from animal production to manure nutrients available for application to cropland is missing. This is a shortcoming of the model, as manure is a source of nutrients reaching the Gulf. However, the Conservation Effects Assessment Project (CEAP) data include manure as a source of nutrients applied to crops, so the process of reconciling the nutrient inputs and outputs associated with the CEAP and REAP datasets helps implicitly capture the nutrient impacts of manure applied to fields and the implications of best management practices (BMPs) such as nutrient management (NM) and structural erosion control (FT) on modifying nutrient loss associated with manure. Our analysis does not, however, address nutrients lost from confined animal operations, including manure handling and storage, or manure nutrients from pastured animals.

Appendix 2: Incorporating CEAP Results Into the REAP Analysis

The objective of this exercise was to use information contained in the Conservation Effects Assessment Project (CEAP) database about the costs and impacts of adoption of best management practices (BMPs) to construct new BMP enterprises to use as inputs into the REAP model. Inclusion of new BMPs allows the Regional Environment and Agriculture Programming (REAP) model to select BMP alternatives for its production enterprises when solving for optimal patterns of agricultural production and production practices under both baseline conditions and under constraints related to nutrient loss and loadings to the Gulf.

The construction of BMP alternatives for REAP involves modifying REAP's existing baseline production enterprises to create a new set of BMP enterprises that reflects projected impacts and costs from BMP adoptions, as described in the CEAP data base. The steps required to reconcile CEAP's data structure with REAP's input requirements are outlined briefly here and elaborated on in the following sections.

CEAP points were first mapped to REAP rotations by excluding those points with non-REAP crops (anything other than corn, soybeans, wheat, cotton, oats, sorghum, rice, barley, silage, and hay) 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 used the CEAP data for each point to calculate the absolute change in impact observed as a result of imposing BMPs on that production system. 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 point within the 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 applied) to meet nutrient-reduction goals. The relative benefits in terms of nutrient reductions depend both on the best management practice applied and on the REAP region's location relative to the Gulf; the delivery coefficients translate each region's activity into impacts on Gulf nutrient loading. Production enterprises with no corresponding CEAP points that could be used to calculate the expected impacts of BMPs within that system were retained in the model but did not have the option to adopt BMPs.

Mapping CEAP Points to REAP Production Enterprises

The CEAP dataset consists of 18,691 data points describing production and management conditions for more than 100 crops throughout the United States. REAP's production input structure, however, is limited to 10 major field crops, which can be produced on 2 soil types (highly erodible and non-highly erodible soils) using dryland or irrigated production and one of three tillage types (reduced, conventional, and no-till). REAP's distribution of baseline crop acreage in the Mississippi/Atchafalaya River Basin (MARB) is shown in Appendix table 2.1. For each of REAP's 273 production regions, crop production can occur under a set of possible crop rotations that has been identified for that region from historically observed rotations in the National Resources Inventory (NRI). Within a REAP region, the combination of rotation, tillage, and irrigation type is referred to as a "production enterprise."

The first task in reconciling the CEAP and REAP input sets was to associate each CEAP data point with an existing REAP production enterprise, where possible.

Appendix table 2.1

Distribution of crop acres in REAP between irrigated (I) and dryland (D) production, by crop

Crop	Production type	Million acres
Barley	D	1.2
Barley	I	0.3
Corn	D	68.0
Corn	I	11.7
Cotton	D	2.1
Cotton	I	1.4
Hay	D	34.9
Hay	I	3.5
Oats	D	2.4
Oats	I	0.0
Rice	D	0.0
Rice	I	0.2
Silage	D	2.7
Silage	I	0.5
Sorghum	D	4.4
Sorghum	I	0.6
Soybeans	D	49.0
Soybeans	I	3.9
Wheat	D	38.0
Wheat	I	3.6

Source: Regional Environment and Agriculture Programming model.

The original CEAP dataset contained production information for 18,691 points. We first excluded any CEAP point that contained in its rotation a non-REAP crop, which left us with 16,578. The remaining CEAP points were assigned a REAP rotation label using the crop history associated with each point. Assignments were made without consideration of the number of times a crop occurs in the rotation; any point with both corn and soybean in the rotation at a given CEAP point was mapped to REAP's Corn-Soybean rotation for that region, as REAP is not able to differentiate between Corn-Soybean and Corn-Corn-Soybean, or Corn-Soybean-Soybean, for instance.

Each CEAP point was then assigned a tillage type based on an average of CEAP's Soil Tillage Intensity Rating over all the years measured for each point. In general, an average rating of 0-20 is assigned to no-till, 20-80 to reduced till, and >80 to conventional till. The tillage assignment is given to the rotation and applies across all crops in the rotation in the REAP production enterprise. CEAP points were then designated as either irrigated or dryland based on applied irrigation levels provided. We did not distinguish deficit irrigation from other forms of irrigation management; any amount of irrigation resulted in a CEAP point being designated as irrigated production.

Calibrating Baseline REAP Impacts to CEAP Impacts

The indicators of management and environmental impact considered in this analysis include:

- Average nitrogen (N) application
- Average phosphorus (P) application
- Sediment loss
- Wind erosion
- Soluble N and P in water runoff
- Sediment attached N and P
- N and P attached to wind erosion[11]
- Soluble N and P in subsurface flow
- Soluble N and P in percolation

To ensure some consistency between the CEAP and the REAP baseline environmental impact conditions (as measured by the indicators above), an effort was made to calibrate REAP's baseline conditions to the baseline conditions observed in the CEAP data. This effort was complicated by the fact that REAP's baseline representation of the agricultural landscape—which crops are grown, in which rotations, and on how many acres by region—differs in several fundamental ways from the CEAP baseline landscape:

- REAP has a limited number of crops—corn, soybean, wheat, hay, rice, barley, oats, sorghum, silage, and cotton—so REAP's modeled landscape does not include acreage that has other crops in rotation.
- The set of production enterprises available for each REAP region has evolved over time, but is largely dependent on an assessment of rotations present in the 2007 National Resources Inventory. As a result, the rotations present on REAP's agricultural landscape differ from those present in CEAP's baseline, which are identified through the CEAP survey. In this analysis, about 33 percent of REAP's production enterprises in the MARB were not able to be matched to CEAP data points; those enterprises accounted for about 23 percent of REAP's baseline production acreage in the MARB.

---

[11] While nutrients attached to wind erosion are calibrated and tracked through the REAP analysis, they are not included in our calculation of nutrients impacting the Gulf through waterborne nutrient loadings.

- The acreage represented for each rotation in REAP is derived from the expansion factor associated with the NRI points, which are aggregated up to the REAP production region level and then reconciled (through a matrix balancing routine) with USDA, National Agricultural Statistics Service (NASS) data on crop acreage by region and (through a separate matrix balancing routine) with tillage information from the NASS-ERS Agricultural Resource Management Survey (ARMS). The acreage expansion factor for each point in CEAP is also calculated by the NRI team to ensure that the acreages by crop are consistent with data derived at a more aggregate level from other sources, but using a different method. The result is that the acreages associated with the different production enterprises are not the same across the two modeling systems. Applying the CEAP expansion factors to the joint CEAP-REAP production enterprises accounts for 191.6 million acres within the MARB, while the acreage estimates used within the REAP modeling system estimates that those joint production enterprises account for 141.6 million acres within the MARB. As mentioned above, the remaining 23 percent of REAP's acreage within the MARB is occupied by rotations with no corresponding CEAP observation point.

The baseline environmental impacts associated with production also differ across the two modeling frameworks. ERS uses the field-level EPIC model to simulate and regularly update crop production and impact estimates based on field operation systems designed many years ago with expertise largely contracted from the Rodale Institute and the World Resources Institute. The CEAP system used APEX, a field-level crop growth simulation model that is also capable of routing water, nutrients, and sediment over landscapes, to simulate crop production and impacts, as well the implications for those environmental indicators of adopting a set of the BMPs. Our goal was to use CEAP's simulated results for BMP effectiveness, together with estimates of cost and yield impact, to design BMP production enterprises for the REAP framework.

We did not attempt to reconcile baseline production acreage differences between the two modeling systems. However, in order to more consistently represent the potential impacts associated with BMP adoption, we calibrated the per-acre environmental impacts associated with production between the two modeling systems to correct for broad-scale differences in modeled impacts across nutrient loss pathways by region.

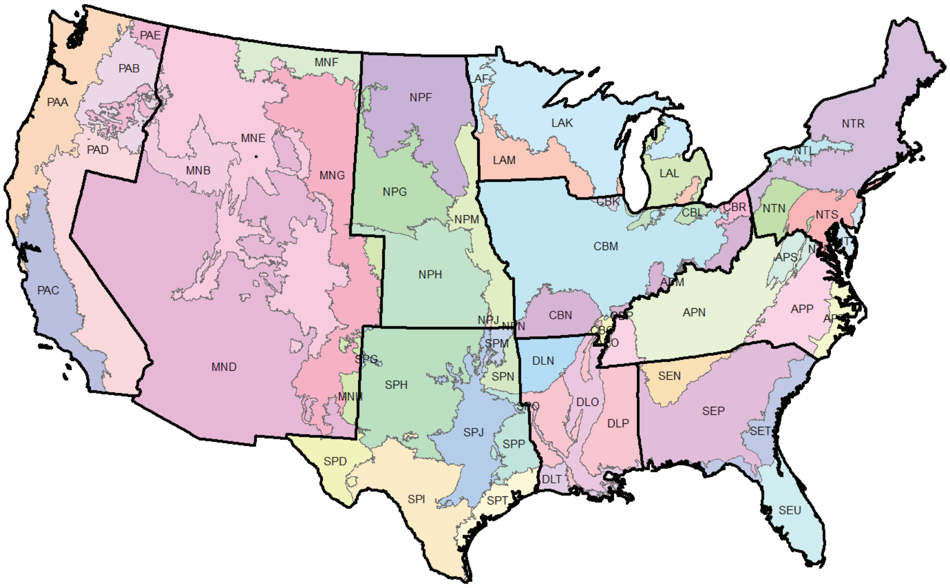
We did not want to limit REAP's input to only those enterprises with corresponding CEAP data, as deleting disjoint production enterprises would unduly restrict the choice set of production possibilities available to the REAP optimization. In order to apply a consistent method of calibration across all of REAP's baseline inputs—those that were represented by the CEAP data as well as those that were not—we calculated regional calibration factors for each of REAP's regions, and applied that calibration factor across all production enterprises within the region.

Calibration factors were calculated based on baseline production information for production enterprises that were common to both CEAP data points and REAP input files at the level of REAP regions aggregated over four-digit hydrologic unit codes (HUCS) (see Appendix figure 2.1).

For each of those regions, the baseline CEAP impact results for all data points that have a corresponding REAP production enterprise were aggregated up to the calibration region level using CEAP's expansion factors for each point. The baseline REAP impact results were aggregated up to the same regional level using REAP's baseline acreage levels for each production enterprise. The calibration factor was calculated as the absolute difference between the per-acre estimates of impact for each of the environmental indicators listed above;[12] separate calibration factors were calculated for highly erodible and non-highly erodible land and for tiled and not tiled production. The baseline REAP impact estimates for all of the production enterprises were then adjusted by those factors. Those factors varied widely by region and indicator (see Appendix figure 2.2 for an example).

Appendix figure 2.1

Regions used in calculating calibration factors for calibrating REAP baseline indicators to CEAP baseline indicator estimates



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service.

By calibrating baseline REAP production impacts to the baseline CEAP production impacts, we create preliminary REAP baseline inputs that implicitly represent the distribution of BMPs across the landscape as simulated within the CEAP baseline data points. The new BMP production enterprises for the REAP model are then created as shifts from the newly calibrated baseline inputs, with the shift factors calculated from the CEAP data. Those BMP production enterprises represent additional practices that are applied to the baseline production enterprises that go above and beyond those practices that were present in the CEAP baseline practices, and whose impacts are implicit in REAP's base impacts.

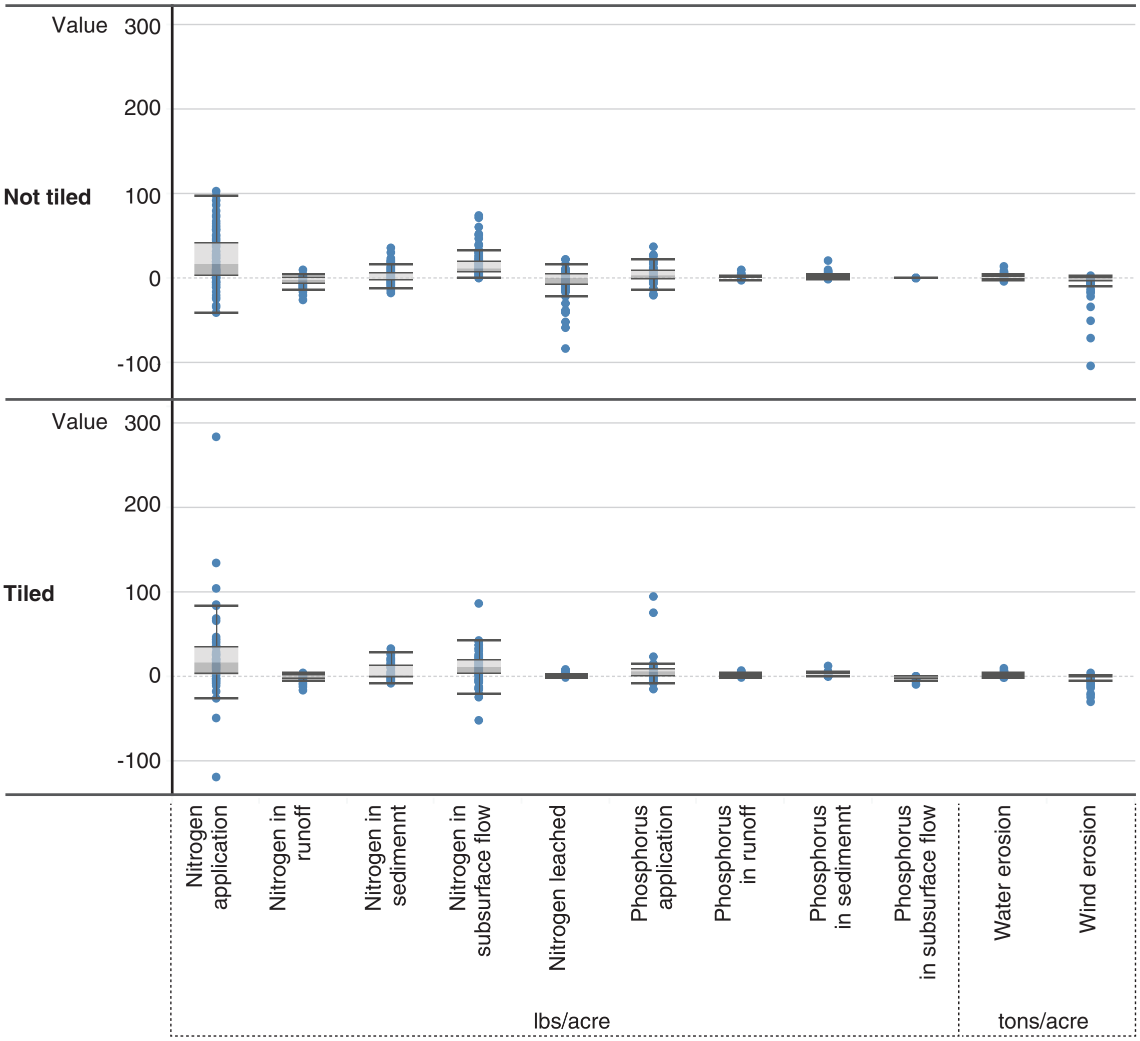
The analytical baseline for this research is then run by allowing the model to optimize over all of the calibrated baseline production enterprises, together with the newly created BMP alternatives for the subset of those production enterprises that are present in the CEAP data. REAP's optimization for the baseline scenario, which includes no nutrient loss constraints, is therefore not limited to the original set of baseline production enterprises, and in fact REAP finds it optimal to allocate a small amount of acreage to some of the newly available BMP production scenarios—i.e., to install a few additional BMPs to the baseline landscape above and beyond what are simulated in the CEAP baseline. REAP finds that additional BMP elements would have been optimal given the 2007 conditions. Several factors could explain why those elements were not represented in the CEAP data:

---

[12] Because of wide swings in nutrient loss allocation between subsurface flow and leaching, and an apparent lack of precision in simulation models' differentiation between these two loss pathways, these two impact estimates were aggregated and calibrated jointly.

Appendix figure 2.2

Distributions of REAP calibration factors for nutrient inputs and losses on tiled and un-tiled cropland



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service.

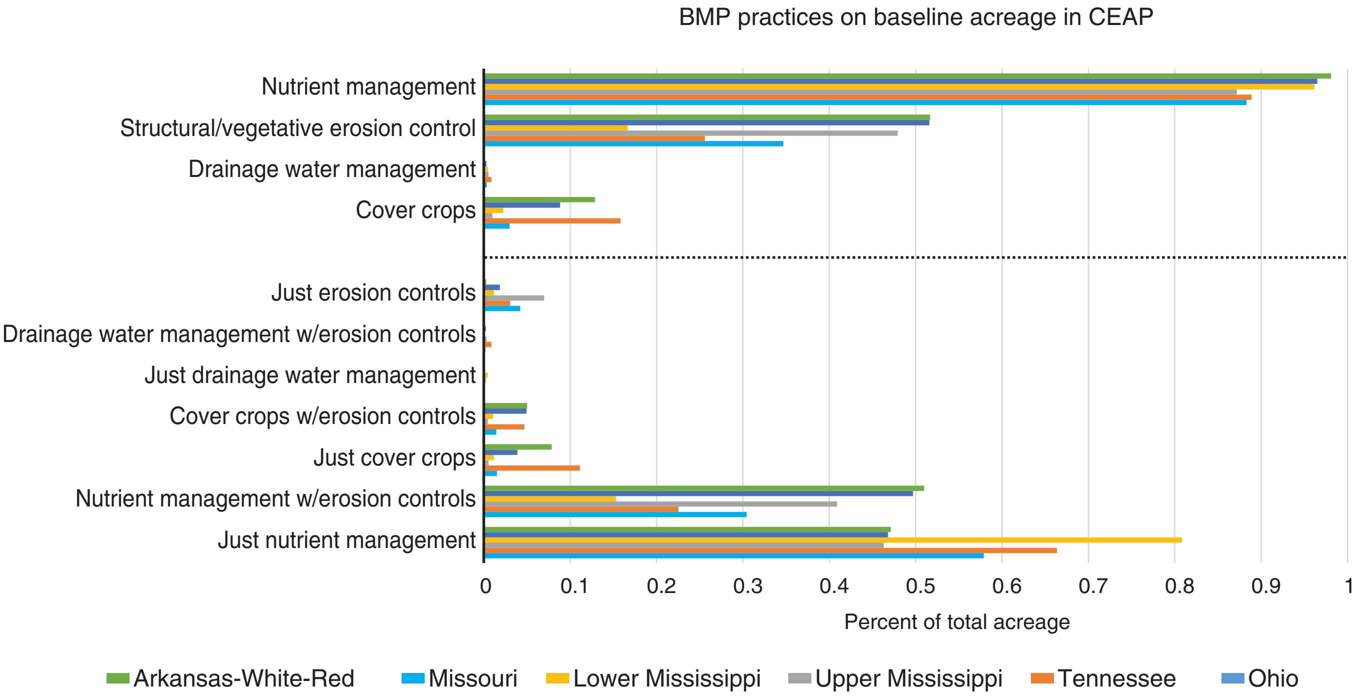
- There are likely obstacles to adoption that are not accounted for in REAP's optimization process—lack of technical assistance, transaction costs, etc.
- There may be a small gap in the representativeness of CEAP's coverage or in the calculation of the expansion factor for certain points.
- Other baseline differences in production factors such as yield may results in slight divergences between CEAP and REAP in the relative profitability of BMP versus base production enterprises.

We cannot constrain REAP to choose only its original base practices in the baseline, as it would bias REAP's internal calculation of land distribution parameters and affect land allocation choices under the constraint scenarios as well. Instead, we generate a hybrid portrait of "baseline" conditions that reflects elements of CEAP's baseline (through the calibration of regional average per-acre impacts) but augments that baseline with additional BMP elements, as dictated by REAP's effort to maximize surplus from agricultural production.

It is difficult to precisely characterize the acreage in specific BMPs in the baseline. For the rotations that REAP and CEAP have in common (and that are therefore used to calibrate REAP's input impact measures), the practices present in CEAP's baseline acreage are shown in Appendix figure 2.3.

Appendix figure 2.3

CEAP (Conservation Effects Assessment Project) baseline acreage by best management practice (BMP) on production enterprises common in the CEAP and REAP



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service from Conservation Effects Assessment Project information.

We apply calibration factors that are calculated based on this distribution of BMPs to REAP's production enterprise impacts, roughly extending those distributional assumptions across the REAP baseline production enterprises. When we run our analytical baseline, REAP augments the extent of CEAP's baseline practices in the MARB as shown in Appendix table 2.2.

Appendix table 2.2

Additional BMPs in the Mississippi/Atchafalaya River Basin (MARB) adopted by REAP optimization in baseline

Nutrient-reduction practices (million acres)	
Nutrient management	13.76
Nutrient management w/erosion controls	0.11
Cover crops	0.05
Erosion control	0.43
Cover crops w/erosion controls	0.02
Drainage water management	1.78
Drainage water management w/erosion controls	0.00

Source: USDA, Economic Research Service.

Because nutrient management and structural erosion control are so widely practiced anyway, the addition of 13.76 and .43 million acres, respectively, is not a substantial shift from the CEAP baseline. The addition of 1.78 million acres of drainage water management (DWM), however, is a substantial shift from the CEAP data, which only reported DWM adoption on 570,000 acres within the baseline.

A comparison of the resulting per-acre N loss and P loss estimates by sub-basin is shown in Appendix figure 2.4. The CEAP estimates are calculated using CEAP's impact estimates weighted by CEAP's expansion factors, while the REAP estimates are calculated using REAP's calibrated impact estimates weighted by REAP's baseline acreage. Note that the CEAP data provided did not include a measure of phosphorus leaching, so leaching only appears in the REAP model's estimates for P losses.

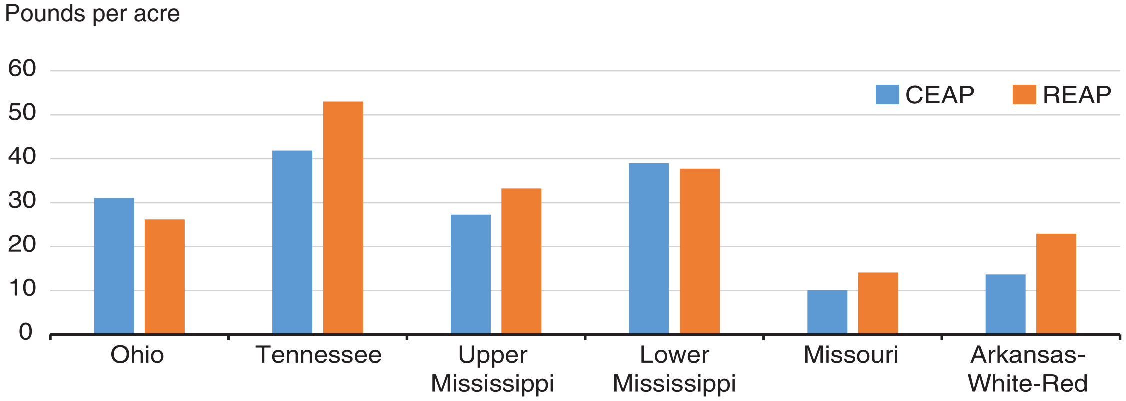
Calculating the Impacts of BMP Adoption at the Scale of the REAP Region

The CEAP database provides simulated results for the impacts of BMP adoption at the level of the CEAP data point. Each of those points is associated with an expansion factor that is estimated to reflect the amount of acreage represented by that specific point. In many cases, multiple CEAP points correspond to a single production enterprise within a REAP region (i.e., there are multiple CEAP data points corresponding to a conventional till, dryland, continuous corn rotation within the boundaries of a particular REAP region). For each of those points, we calculated yield and environmental impact factors associated with each of the BMPs applied to that point. For measures of yield and environmental impact, we calculated the absolute change in impact as a result of imposing each BMP (i.e., the difference between CEAP's baseline condition and that projected after application of the BMP).

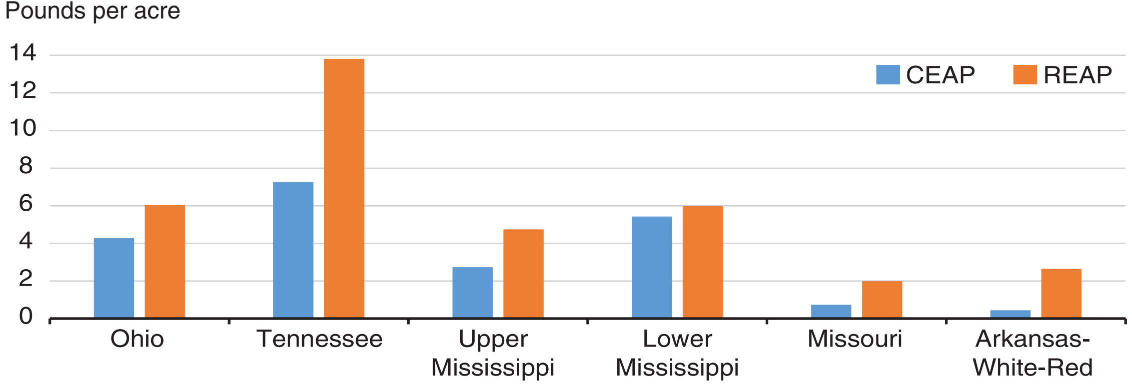
Appendix figure 2.4

Per-acre nitrogen and phosphorus losses by sub-basin

Average nitrogen losses



Average phosphorus losses



Notes: REAP = Regional Environment and Agriculture Programming (model). CEAP = Conservation Effects Assessment Project.
Source: USDA, Economic Research Service.

To calculate representative BMP impacts per production enterprise at the level of the REAP region, we estimated average yield and environmental impacts from the CEAP data points within the relevant area, weighted by each point's expansion factor. Impact factors were calculated at two scales: at the level of the REAP region, and at a coarse-scale level, at which regions were aggregated up over the watershed designations to form 92 larger calibration units defined by farm production region, land resource region, and soil type (equivalent to the regions illustrated in Appendix figure 2.1 but subdivided into highly erodible and non-highly erodible soils). Those acreage-weighted impact factors were applied to the relevant REAP base production enterprise (according to the mapping described earlier) to construct a set of BMP alternatives for those baseline enterprises, with appropriate yield and environmental impact adjustments. For REAP base production enterprises with a directly corresponding CEAP impact factor (i.e., a CEAP observation point within the same REAP region), the REAP region impact factor was employed in construction of the BMP alternative enterprise for each of the corresponding REAP base enterprises. For those base enterprises without a corresponding CEAP impact factor at the REAP region level, the coarse-scale impact factors were used, if they exist, in production of the BMP alternative enterprises. Those base production enterprises with no corresponding CEAP BMP impact factor at either scale were retained in the model but did not have the option to adopt BMPs.

The production costs associated with production enterprises that adopt BMPs are adjusted in a number of ways. In many cases, CEAP BMPs are associated with varying amounts of “set-aside” acreage (i.e., acreage taken out of production for filter strips or terracing). In those cases, when constructing the alternative BMP enterprise, the existing variable cost categories associated with a baseline REAP production enterprise (fertilizer costs, seed costs, etc.) were scaled down by the percentage of the set-aside to account for land removed from production in determining the magnitude of costs for the BMP enterprise. Yields, and therefore revenues, under the BMP were also assumed to decline by that amount. Some of the CEAP BMPs are also associated with a decrease in nitrogen application; in such cases, the costs of nitrogen are adjusted accordingly when creating the BMP alternative for the REAP baseline enterprise. The CEAP data also provide a cost for each BMP that represents an annualized cost of practice installation and maintenance. An average cost associated with each BMP for a given production enterprise in a region was calculated from the CEAP data point estimates using each point’s expansion acreage as a weighting factor. That cost was also included in the per-acre production costs associated with each alternative BMP enterprise.

Appendix 3: Riparian Buffers and Restored Wetlands—Data and Modeling Assumptions

Here we outline data sources and assumptions used in developing REAP model coefficients for riparian buffer and wetland restoration practices that complement the CEAP model data for within-field practices. The water-quality impact (e.g., quantities of nutrients removed) depends on the land area that can be converted to buffers and wetlands, associated upslope drainage or "treatment" area, the quantities of nutrients that pass through, and nutrient removal rates by practice. The areas that can be converted to buffers and wetlands are derived from spatial data on water courses, cropland area, and extent of tile drainage and buffer coverage. The quantities of nutrients reaching a segment of buffer or wetland reflect the size of the treatment area (e.g., drainage area feeding each buffer and wetland)—conservatively estimated from supporting analyses—and nutrient and soil losses on the treatment area, which are endogenously simulated based on regional crop allocations and cropping systems. Percentage removal rates for nutrients and sediment are drawn from multiple field-level and regional analyses. Costs of implementing conservation measures are based on historical USDA conservation program data.

Riparian Buffers

Area estimates—buffer and treatment area

Area approximations for potential buffer acreage expansion in the MARB and associated cropland area treated were developed from a Geographic Information System (GIS) spatial analysis of cropland covers and water bodies. Primary data sources and assumptions used in GIS-derivation of area estimates are outlined below.

Water courses. We focused on "perennial streams" (stream class codes 46000 and 46006), as well as "intermittent streams" (code 46003), which are typically dry along stretches of the summer growing season. Water courses were identified in the U.S. Geological Survey's National Hydrography Dataset (NHD), using the high-resolution version of NHD hydrography coverages. Area approximations for buffer and treatment acreage were estimated separately for: (1) parcels adjoining perennial streams, and (2) parcels adjoining perennial and/or intermittent streams (or incremental effect of intermittent streams) to avoid double-counting of cropland area. We assumed that buffers along water courses such as ponds, lakes, and existing wetlands would not substantially affect hypoxia in the Gulf, though there may be local impacts. Smaller ephemeral streams are also excluded as they are not likely to be the focus of buffer initiatives despite their capacity to transport nutrient loads during peak storm events.

Cropland stream parcels. The 2014 USDA-Farm Service Agency (FSA) Common Land Unit (CLU) dataset is used to identify cropland parcels within the MARB that adjoin (or are traversed by) perennial and intermittent streams identified in the NHD. Area estimates for stream parcels reflect acreage in FSA program crops, or crop commodities eligible for Federal program supports in the recent past, identified in the CLU database. Estimates include unique acreage that explicitly avoids double-counting of fields with multiple crops grown during the crop year. For the modeling analysis, regional buffer and treatment acreage derived from CLU data is expressed as percentage area shares to allow for differences with REAP-modeled crops and cropland area.

Buffer area. Acreage potentially available for buffer expansion is estimated from identified cropland stream parcels within the MARB. The USDA-National Agricultural Statistics Service's Cropland Data Layer (CDL), developed from satellite imagery for the 2014 cropping season, is used to assess land cover within stream margins—defined as cropland portions falling within 30 meters (98.4 feet) of a water course. The 30-meter buffer width, reflecting the size of a single 30-meter grid pixel used to assess CDL land cover characteristics, is reasonably representative of buffer width requirements under USDA financial assistance programs. We do not include in our analysis other non-cropland covers (e.g., pasture, shrubland, wetland) that could be improved (e.g., planted to trees) to enhance buffer effectiveness.

Cropland parcels adjoining perennial streams have generally higher levels of existing buffer coverage relative to intermittent streams. Perennial streams typically follow parcel edges, while intermittent streams are more likely to intersect cropland parcels. Farmers may be less inclined to install buffers along intermittent streams for various reasons (e.g., loss of cultivated cropland area, restrictions on field design and reduced field access, potential tree shading on crops, aesthetic preferences for field orderliness, and underestimation of intermittent stream loading potentials). In our analysis, we allow for buffer expansion along both perennial and intermittent streams, consistent with cropland eligibility standards for forested riparian buffers under the Environmental Quality Incentives Program.

Treatment area. Buffer treatment area—or the upslope portion of a cropland parcel that drains through an installed riparian buffer—is estimated as acreage in stream parcels less stream margin acreage, adjusted by the portion of margin acreage converted to buffer by region. For each region, the buffer treatment area as measured in acres is then converted to a figure representing the percentage of cropland treated in the region per acre of buffer.

In reality, the area effectively treated by buffers may represent only a partial share of the remaining cropland parcel acreage; or in some cases, the treatment may extend beyond a single parcel to include adjacent upslope cropland. While our measure of treatment area represents a crude approximation of potential cropland treated by buffer expansion, it offers a reasonable estimate for purposes of this modeling analysis.

Soil erodibility designations. Area approximations for expanded buffer and treatment areas are estimated separately for non-highly erodible (NHEL) and highly erodible (HEL) cropland parcels, based on the 2014 FSA CLU database. Nutrient and sediment losses generally differ across NHEL and HEL, reflecting higher erosion rates on HEL soils and resulting differences in conservation and cropping systems. In addition, HEL cropland stream parcels are more likely to be buffered—either naturally (e.g., wooded hillslopes) or through increased rates of installed buffers, due in part to compliance requirements for obtaining USDA farm program payments and financial assistance for implementing conservation practices on highly erodible lands. While CLU-derived area estimates for NHEL and HEL cropland differ somewhat from NHEL/HEL breakouts in REAP (derived from the USDA Natural Resources Conservation Service's National Resources Inventory), we assume that percent acreage shares based on the CLU data are applicable for the buffer analysis.

Incorporation in the REAP model. Estimates of potential cropland conversion to riparian buffers are converted to area-weighted acreage shares for NHEL and HEL cropland by REAP region. Cropland stream margins along perennial and intermittent streams are assumed to enter the solution in fixed proportions. Cropland reductions due to buffers are assumed in addition to conservation set-aside assumptions for CEAP within-field practices, with total set-aside area adjusted to account for potential double-counting. While buffer expansion alone may not significantly affect cropland area (particularly as regional cropland supply constraints are not generally binding), consideration of buffers in combination with wetland restoration and other conservation set-asides can have a measurable impact on cropland in production. REAP's optimization, which incorporates a consideration of buffer costs (described below) and forgone production returns, then endogenously selects the optimal regional extent of cropland-to-buffer conversion, and associated buffer treatment area, to meet nutrient discharge targets for each scenario.

Buffer effects on nutrient-loss parameters

Buffers affect nutrient field loss through surface runoff of particulate material (sediment and organic matter), dissolved (soluble) nutrients through surface runoff, subsurface flows of dissolved nutrients, and tile drainage flows. The effectiveness of buffers in our analysis is measured as a percent reduction in edge-of-field losses by discharge pathway. Model assumptions for nitrogen and phosphorus are as follows, with a brief discussion of assumptions below.

Appendix table 3.1

Assumed percent reductions in edge-of-field losses from installing buffers

Nutrient discharge pathway	Nitrogen	Phosphorus
Surface runoff (particulate matter)	20%	20%
Surface runoff (soluble)	20%	0%
Subsurface flows	35%	0%
Tile drainage	0%	0%

Nitrogen discharge. Model assumptions on buffer effectiveness for nitrogen loss reductions are largely informed by Mayer and colleagues (2005), which presents an EPA meta analysis of buffer studies on nitrogen control. Representative N reductions across land covers and discharge pathways ranged from roughly 50 percent for a 3-meter (m) buffer width to as high as 75 percent for a 28-meter buffer width (Mayer et al., 2005). Our model analysis assumes a 30-meter planted buffer, with forested cover along perennial streams and grassed cover along intermittent streams. However, as our GIS assessment of nonbuffered fields cannot accurately assess existing distance from stream to field edge within a 30-m pixel for cropland stream parcels, the difference in load reductions of 50 percent (3 m) and 75 percent (28 m), or 25 percent, may be more representative of the average *change* in load reductions. In addition, the EPA assessment notes considerably greater buffer effectiveness for capture of subsurface nitrogen than for nitrogen in surface runoff (Mayer et al., 2005). Consequently, we adjust loss reductions accordingly, with reductions for N in surface runoff of particulate and dissolved N (20 percent) considerably less than reductions for subsurface flows (35 percent), including both lateral flows and deep percolation below the root zone. We assume that buffers have no effect on tile drainage flows on tiled fields. While our model assumptions for N loss reduction are set lower relative to reported results in Mayer and colleagues (2005), we chose more conservative estimates of reduction efficiency to account for various factors that limit potential gains—e.g., time required for forested buffers to achieve full effectiveness, reduced buffer effectiveness in capturing nutrients in high-volume stormwater runoff, declines in effectiveness of established buffers over time due to soil-nitrogen accumulation, flushing of soil-nitrogen during periods of water saturation, formation of gulley erosion from repeated storm events, or increasing contributions of organic nitrogen from tree and brush cover.

The existence of tile drainage is an important consideration influencing the effectiveness of riparian buffers. The REAP model includes acreage shares for tiled and non-tiled cropland by region, based on reported data from the 2012 Census of Agriculture. Nutrient losses are simulated in the Environmental Policy Integrated Climate (EPIC) model for crop production under both tiled and nontiled field conditions. Loss coefficients are then area-weighted in the REAP model to reflect cropland shares with and without tile drainage. For fields with tile drainage, we assume that installation of buffers has no effect on N discharge through tile drains—which accounts for much of the total N loss from tile-drained fields. We further assume that the percentage N loss reductions through other pathways—including surface and (nontile) subsurface flows—apply uniformly to tiled and nontiled fields.

In the REAP modeling analysis, the effect of buffers on aggregate nitrogen loadings reflect area treated by cropland buffer conversion, the regional extent of tile drainage, and N loss reduction factors by nutrient discharge pathway. Buffer impacts are also a function of the intensity of cropland production and conservation investments within the upslope buffer treatment area. Buffers may offset the effect of nitrogen-intensive cropping systems, while conservation practices that lessen upslope nutrient runoff may effectively limit nutrient loading reductions attributable to buffers.

Phosphorus discharge. While the study emphasis is on nitrogen—the primary contributor to hypoxia in the Gulf—we also incorporate buffer-related changes in phosphorus (P) loadings. Model assumptions for phosphorus discharge reductions were based primarily on Dodd and Sharpley (2016), which provides a broad review of recent studies examining the effect of conservation practices for phosphorus control. In general, the studies suggest that buffers result in fairly strong reductions in particulate phosphorus in surface runoff but fairly low (or even negative) reductions for dissolved phosphorus due to the buildup of soil P over time. Consequently, we assume a reduction in phosphorus adjoined to soil in surface runoff (20 percent), equivalent to the reduction in surface flow N. For all other discharge pathways involving dissolved P, both surface and subsurface flows, we assume that buffers have no long-term effect. As in the case of nitrogen, our model assumptions for achievable phosphorus discharge reductions are conservative relative to reported findings, based on reasons cited above.

Buffer costs

Buffer cost assumptions are based on NRCS State-level costs supporting buffer practice payments under EQIP for FY2011. We apply the cost of riparian forest buffers (practice code 391) to perennial streams and the cost of riparian herbaceous (grass) cover (practice code 390) to intermittent streams, and costs are area-weighted based on the relative shares of potential buffer acreage expansion along perennial and intermittent streams by REAP region. Buffer costs vary widely by State, with considerable variation across reported options within States for forested and herbaceous buffers. Representative State-level costs were estimated based on a simple average of reported costs across buffer options, as information was not available on predominant buffer type by State. State-level costs were then assigned by REAP region, using the State that most closely aligns with model regions. In cases where buffer practice costs were not reported for a given State in FY2011, costs were applied from an adjacent State with acreage in the region and generally similar production conditions.

Modeled costs for buffers reflect the annualized cost of the initial buffer installation plus annual maintenance charge, expressed per cropland acre converted to buffer. Reported discount rate and practice life assumed in the NRCS State-level cost estimates vary somewhat across States. We apply a representative discount rate of 5 percent, consistent with CEAP time-discount assumptions. Practice life is set at 15 years for riparian tree buffers and 10 years for herbaceous buffers. While cropland stream buffers are generally installed with USDA financial assistance, reflecting the offsite nature of buffer benefits, cost estimates in our study represent the full cost of installation with no adjustment made for cost-share payments. Forgone production returns associated with buffers are captured in the model solution and are not explicitly considered in buffer cost calculations.

Restored Wetlands

Area estimates—wetland acreage and treatment area

Potential for wetland restoration in the MARB reflects the extensive losses in wetland acreage, with roughly 40 million acres of tile-drained cropland within the MARB based on the 2012 Census of Agriculture. Much of the cropland in the MARB is underlain by shallow and impermeable subsoils that restrict the downward percolation of water. With downward movement limited, subsurface waters move more horizontally through the watersheds, feeding wetlands and other water bodies. In some areas, natural subsurface flows keep topsoils suitable for crop production. Elsewhere, high water tables may limit or preclude crop cultivation on the land. Tile drainage installed to drain wetlands increases the rate of subsurface flow, with water routed to drainage channels that discharge to surface-water bodies.

Restored wetland area. We assume that wetlands can be restored most cost-effectively on tile-drained acreage receiving water from a sizeable drainage area, most likely by plugging tile drains and planting suitable vegetation. We assume that no more than 1 percent of the tiled cropland acres by county—representing optimal sites for wetland restoration—can be restored. Given that there are roughly 40 million tile-drained cropland acres in the MARB, total potential wetland creation in the analysis is capped at approximately 400,000 acres with regional acreage caps reflecting the spatial distribution of tiled acreage.

Treatment area. A wide range of wetland-to-treatment area ratios are found in the literature, reflecting variation in local cropland density and determinants of hydrologic flows (e.g., topography, soils, weather, and conveyance structures). For purposes of our analysis, we assume a wetland-to-treatment area ratio that varies, by region, between 1:18 and 1:25. This is roughly consistent with acreage assumptions in Christianson et al. (2013), which assumes 1 acre of restored wetland plus 3.5 acres of wetland buffer treat 100 acres of drainage area (combined wetland/buffer-to-treatment area ratio of 1:22). Wetland buffers capture sediment that can shorten the life of restored wetlands and are generally recommended in wetland restoration projects. Our model does not include wetland buffers explicitly, so a relatively conservative wetland-to-treatment area ratio was used to help ensure that wetlands' effectiveness are not overstated.

Wetland effects on nutrient loss parameters

In our analysis, the effectiveness of restored wetlands as a nutrient control measure is represented as a percent reduction in edge-of-field losses for treated area within the wetland drainage. Model assumptions for nitrogen and phosphorus by discharge pathway are shown in Appendix table 3.2.

Appendix table 3.2

Assumed percent reductions in nutrient losses from restored wetlands

Nutrient discharge pathway	Nitrogen	Phosphorus
Surface runoff (particulate matter)	40%	20%
Surface runoff (soluble)	40%	0%
Subsurface flows	40%	0%

Nitrogen discharge. The effectiveness of wetlands in controlling nutrient loss ranges widely across restored and constructed wetlands under varying local conditions. Research has estimated wetland nitrogen removal rates as low as 9 percent and up to 100 percent (Fennessy et al., 1994; Kadlec and Hey, 1994; Phipps and Crumpton, 1994; Kovacic et al., 2006; Xue et al., 1999; Fink and Mitsch, 2004; Crumpton et al., 2006; Mitsch et al., 2005). We assume a 40-percent removal rate for nitrogen, applied uniformly across nutrient discharge pathways. The 40-percent N removal rate is reflective of, if somewhat lower than, reported average measures reported in Tomer et al. (2015) and the Chesapeake Bay Program (2016), helping to ensure that wetland benefits across the MARB are not overstated.

Phosphorus discharge. In general, the studies suggest that while restored wetlands can intercept phosphorus discharges within the drainage area, the long-term effectiveness of wetlands as a P sink may be lessened over time. In contrast to nitrogen inflows—which may be more fully utilized by plants or lost to the atmosphere through denitrification—excess phosphorus accumulation is more likely to result in soil P saturation. Consequently, we assume a lesser reduction in particulate phosphorus in surface runoff (20 percent), similar to particulate P reduction assumed for riparian buffers. For all other discharge pathways involving soluble P, both surface and subsurface flows, we assume that restored wetlands have no long-term effect. As in the case of nitrogen, our model assumptions for achievable phosphorus discharge reductions are conservative relative to the range of reported findings.

Wetland cost

We estimated a wetland restoration cost model using primary USDA Wetland Reserve Program (WRP) contract records. Under WRP, USDA purchased permanent easements on cropland restored to wetland conditions. The restoration costs reported in the contract data are agreed-upon amounts—actual costs may differ. We assumed that these amounts are reasonable approximates of actual cost, which reflect the value of forgone production. As with buffers, we do not assume any adjustments for cost-share payments. Estimated wetland restoration costs were incorporated within the REAP model in a three-step process. Based on the observed distribution of county-level costs across the MARB, we defined three wetland cost categories: Low (less than $600/acre), Medium ($600 to less than $750/acre), and High ($750/acre or more). The cost categories allow the model to select from least-cost options for wetland restoration within a given region. We then calculated an average cost and associated acreage share for each of the three cost-category ranges by REAP region, based on an area-weighting of tile-drained cropland by county from the 2012 Census of Agriculture. Finally, wetland restoration costs were expressed as annualized costs for use in the model analysis. In calculating annualized costs, we assumed a wetland service life of 15 years and discount rate of 5 percent, consistent with NRCS-EQIP assumptions for wetland restoration practices.