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METHODS

# Nitrogen sources and Gulf hypoxia: potential for environmental credit trading☆

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## Abstract

A zone of hypoxic and anoxic waters has become a dominant feature of the northern Gulf of Mexico. Nitrogen draining into the Gulf from the Mississippi Basin has been identified as the primary source of the problem. Reducing nitrogen loads from point and nonpoint sources in the basin is the primary goal of an action plan developed to address the problem. In this paper, we use data on point source dischargers and a model of the agriculture sector to examine whether the purchase of nitrogen reduction "credits" from nonpoint sources would reduce the cost of nitrogen control if point sources are required to reduce nitrogen discharges. Results indicate that a substantial degree of credit trading could affect agricultural commodity prices, thereby affecting agricultural production outside the basin.

*Keywords:* Hypoxia; Nitrogen; Credit trading; Economic modeling

A zone of hypoxic (<2.0 mg/l of dissolved oxygen) waters has become a dominant feature of the northern Gulf of Mexico. Analyses of sediment cores from the Louisiana Shelf indicate that the increased eutrophication and hypoxia are the result of increased nitrogen loadings from the Mississippi River (Rabalais et al., 1996). In 1998, Congress enacted the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998, which called for establishment of an interagency task force that would conduct a scientific assessment of causes and consequences of hypoxia in the Gulf of Mexico and develop a plan of action to reduce, mitigate, and control hypoxia (CENR, 2000). Reducing nutrient loads from point and nonpoint sources in the Mississippi drainage basin was a primary goal of the resulting action plan (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). Reducing nitrogen loads would, not only reduce

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☆ The views expressed in the paper are the authors' and do not necessarily reflect those of the U.S. Department of Agriculture or the Economic Research Service.

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hypoxia in the Gulf, but also improve water quality within the basin as well.

We used a mathematical programming model to explore point–nonpoint trading as a potential policy tool for reducing nitrogen loads entering the Gulf via the Mississippi River. We designed a regionally based trading program within the Mississippi Basin and used the model to estimate the price of a marginal trade within each subregion, the impacts on the agriculture sector, and the welfare effects. We expect that allowing point sources to purchase nitrogen reductions from agriculture will reduce their costs for meeting potential nitrogen reduction goals and provide an incentive for nonpoint sources (agriculture) to implement nitrogen-reducing best management practices. If there is a large difference in the costs of reducing nutrient loads, then point–nonpoint source trading could be an option in at least some portions of the watershed.

## 1. Background

The Northern Gulf of Mexico hypoxic zone represents one of the largest zones of oxygen-deficient bottom waters in the western Atlantic Ocean. At its peak, this zone stretches along the inner continental shelf from the Mississippi Delta westward to the upper Texas coast. The average extent of the hypoxic zone between 1993 and 2002 was about 17,000 km$^2$ (LUMCON, 2003). In 2002, the zone attained a maximum measured extent of 22,000 km$^2$. Large loads of inorganic nitrogen carried by the river, particularly during the spring, have been identified as the primary cause of nutrient enrichment that leads to the formation of hypoxic waters (CENR, 2000).

There are a number of sources of nitrogen in the Mississippi Basin, including municipal and industrial point sources, commercial fertilizer and animal manure used on cropland, septic systems, and atmospheric deposition. Agricultural nonpoint sources are estimated to contribute more than 65% of the nitrogen loads to the Gulf in the outflow of the Mississippi and Atchafalaya rivers, and all point sources 11% (Goolsby et al., 1999). It is important to note that the conversion of wetlands to agricultural and other uses and the installation of tile drainage systems have contributed to the high nitrogen contribution from agriculture (Mitsch et al., 2001).

The policy context has an important bearing on the feasibility and design of a trading program. Under the Clean Water Act, point source discharges are subject to national regulatory policies that place requirements on pollution control technology or on the quality of effluent. Discharges are regulated at the outlet pipe through permits of the National Pollutant Discharge Elimination System (NPDES). All point sources are subject to these permits.

Nonpoint source pollution is the responsibility of the States through the Nonpoint Source Program (Section 319) (U.S. EPA, 1996). Most States have opted for nonpoint source control programs based on voluntary approaches that rely on education, technical assistance, and financial incentives (ELI, 1997).

Given the current nature of pollution control laws, it is far easier to control point sources than nonpoint sources to achieve a particular water quality goal but not necessarily more cost-effective. Improvements in water quality could be achieved by tightening existing discharge permits, but there is evidence that the marginal costs of additional point source controls are much higher than for nonpoint source controls in many places (National Commission on Water Quality, 1976; Apogee, 1992; Malik et al., 1992; Camacho, 1992). In addition, as noted above, most of the problems in the Mississippi Basin are from nonpoint source agricultural runoff. A trading program would allow point sources to purchase reductions in pollutant loadings from nonpoint sources, reducing the overall cost of pollution control.

An extensive literature has developed on the conditions needed for successful trading between different sources and how the characteristics of nonpoint sources might affect the structure of a trading program, including stochastic processes and asymmetric information (Bartfeld, 1993; Hoag and Hughes-Popp, 1997; Letson, 1992a,b; Malik et al., 1993; O'Neil et al., 1983; Horan et al., 1999; Woodward and Kaiser, 2002; King and Kuch, 2003). Only a few studies, however, have moved beyond the purely theoretical and taken an empirical look at the merits of point–nonpoint trading for water pollution control. Letson et al. (1993) assessed the feasibility of point–nonpoint source trading for managing agricultural pollution loads to coastal areas but based their assessment on a screening tool that included relative significance of nonpoint and point sources, number and types of point sources, and characteristics of agriculture and land use. Potential savings in pollution control costs were not examined.

A study of the Honey Creek watershed in Ohio found that trading had a small potential to reduce the cost of phosphorus control (DPRA, 1986). A study of the potential for trading in the Wicomico Basin in Maryland found that significant cost savings for phosphorus control were possible (Industrial Economics, 1987). In neither of these two cases was a trading program actually established.

A trading program between point sources and urban nonpoint sources was established for the Dillon Reservoir in Colorado in 1984. Engineering studies and a cost minimization model indicated that phosphorus removal goals could be achieved at least cost by combining urban runoff controls with some additional treatment for one of the four treatment plants in the basin (Apogee, 1992). No trades actually occurred because point sources were able to reduce phosphorus loads more cheaply than expected.

Anticipation of high compliance costs to point sources for meeting the nutrient goals in the Tar-Pamlico basin in North Carolina led to a 1990 strategy that includes point–nonpoint nutrient trading. Costs to point sources for meeting nutrient goals were estimated at between $50 and $100 million (Apogee, 1992). The estimated cost of achieving the nutrient reduction goal using agricultural BMPs alone was $11.8 million (U.S. EPA, 1994). This program has not yet resulted in any trades (King and Kuch, 2003).

Current and proposed trading programs have been small in geographic scope, so an assumption that commodity prices would not change has been reasonable thus far. In the case of Gulf Hypoxia, the region requiring management contains a large share of national production of major field crops. Any effort to induce changes in production practices might affect commodity prices. The impacts of a trading program could therefore spill over to other regions and to those not directly involved in the program, including consumers. Based on evaluations of conservation programs, payments to the agriculture sector for implementing conservation measures can affect both the intensive and extensive margins of production, resulting in shifts in production and impacts on commodity prices if the scale of the program is large enough (Young and Osborn, 1990; Doering et al., 1999). Such impacts have a bearing on the welfare implications of a trading program.[1]

## 2. Trading policy for reducing N loads in the Mississippi Basin

The hypoxia problem in the Gulf meets the conditions necessary for trading to be a potential policy tool (Bartfeld, 1993). Both point and nonpoint sources are significant contributors to total nitrogen loads in the basin. Point source abatement costs are likely greater than nonpoint source abatement costs due to reductions in discharges already made by point sources since the passage of the Clean Water Act in 1972. Nonpoint sources significantly outnumber point sources in most regions, resulting in a large pool of potential trading partners.

For this analysis, we assume that all point sources discharging nitrogen (N) in the Mississippi Basin install advanced nutrient removal technology to comply with more stringent NPDES permits. This is one of the suggested components of the hypoxia reduction plan developed after the CENR assessment (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). With trading, the point source would be allowed to offset its required nitrogen discharge reduction by purchasing reductions from agriculture. Farmers can enter into trades with point sources by implementing BMPs that reduce expected nitrogen loadings.

In this analysis, nitrogen reduction credits can be purchased on a one-to-one basis (one unit of point source N discharge reduction for one unit of expected N edge-of-field loss reduction). We selected a one-to-one trading ratio for reasons of simplicity. Relatively little has been written on efficient trading ratios (Malik et al., 1993; Horan et al., 1999). Existing

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[1] Recently, the World Resource Institute released results of a study looking at Gulf hypoxia and potential for trading using the model developed by ERS and described in this paper (Greenhalgh and Sauer, 2003). Their analysis used average cost pricing for credits that is imposed exogenously (rather than marginal cost pricing estimated in the model) and did not consider basin-wide trading.

point–nonpoint trading programs employ trading ratios that are arbitrarily selected under the assumption that point sources should be required to replace one unit of certain discharges with multiple units of uncertain nonpoint source discharges. However, Horan et al. showed that, due to risk and variance features of nonpoint source discharges, the optimal point–nonpoint trading ratio may be less than 1 or greater than 1. This is an empirical question that we could not address with available data.

## 3. Modeling the supply of nitrogen credits from agriculture

The supply of N reduction credits from agriculture and subsequent adjustments in the agriculture sector were estimated with the U.S. Agriculture Sector Mathematical Programming (USMP) regional agricultural model. The USMP is a spatial and market equilibrium model designed for general purpose economic and policy analysis of the US agricultural sector. The economic units analyzed within USMP include products, inputs, geographic areas, and supply/demand markets. The model also estimates soil erosion and nutrient losses to surface runoff, leaching, and the atmosphere using the EPIC model (Williams et al., 1990). USMP has been applied to a variety of issues, including export levels and variability (Miller et al., 1985), trade agreements (Burfisher et al., 1992), imports (Spinelli et al., 1996), input taxes (Peters et al., 1997), irrigation policy (Horner et al., 1990), ethanol production (House et al., 1993), wetlands policy (Heimlich et al., 1997; Claassen et al., 1998), sustainable agriculture policy (Faeth, 1995), nitrogen management (Doering et al., 1999), agrienvironmental policies (Claassen et al., 2001), and manure management policy (Ribaudo et al., 2003).

USMP's geographic units are 45 model regions formed by the intersection of the 10 USDA farm production regions and 20 land resource regions (Fig. 1). For the purposes of this study, we further divided the 45 USMP regions into two groups: those inside the Mississippi Basin (23 regions) and those outside the Basin (22 regions) (two regions within the Gulf were not included in the analysis because of insufficient economic data). Because the USMP regions do not follow watershed boundaries, the allocation is not precise. However, the most important crop-producing regions in the Mississippi Basin are wholly included in the USMP interpretation of the Basin. Trades are restricted to point and nonpoint sources within each USMP region (interregion trading is not allowed). Restricting trades to within regions ensures that

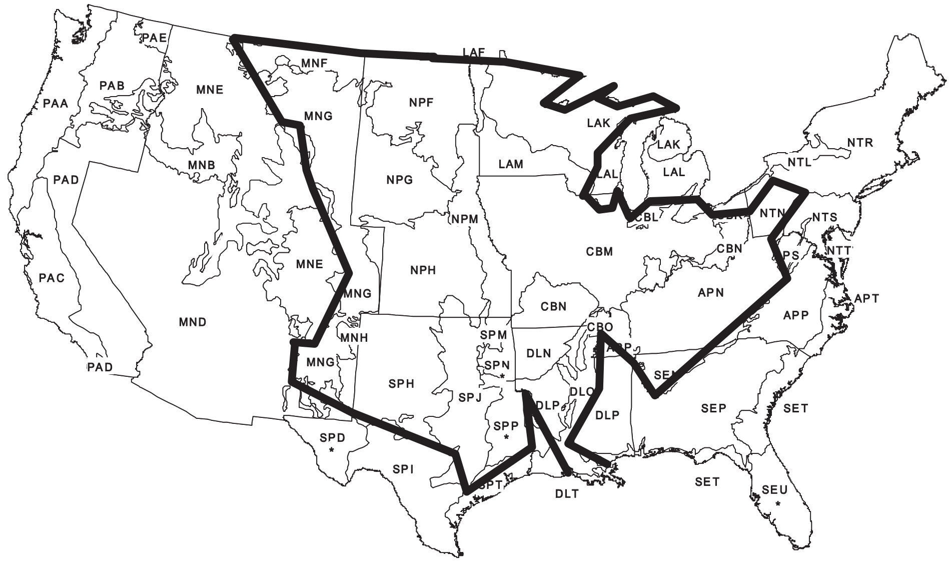

Fig. 1. USMP regions. Regions comprising the Mississippi Basin include: NTN, LAF, LAK, LAM, CBM, CBN, CBO, NPF, NPG, NPH, NPM, APN, SEN, DLN, DLO, SPH, SPJ, SPM, SPP, SPN, MNF, MNG, MNH.

reductions in N loss have the same marginal impact on Gulf hypoxia.

Farmers in each region were assumed to be able to supply N reduction credits by changing fertilizer application rates, changing production practices, growing different crops, or retiring cropland. The amount of credits produced is equal to the difference between N loss to ground and surface water in the base solution of the model and N loss from an alternative production strategy. The cost of supplying these credits is the difference in net returns given constant output and input prices. The greater the reduction in N losses, the greater the loss in net returns (or the higher the price for N reduction credits).

One method for supplying N reduction credits which we did not model is creating wetlands to act as a nitrogen buffer (Mitsch et al., 2001). Wetlands can act as buffers, trapping nitrogen contained in runoff and processing it through plant uptake or denitrification. Wetlands also provide additional environmental service, including habitat for wildlife. This option was not included in the analysis because research indicates that, at the farm level, where the decision to provide N reduction credits is made, it is generally more expensive than changes in fertilizer management (Ribaudo et al., 2001). However, from a regional management perspective, targeting wetland restoration to key subbasins could be more cost-effective than fertilizer management (Ribaudo et al., 2001). The kind of cooperative behavior farmers would need to undertake effective wetland restoration could not be modeled in the USMP framework.

## 4. Modeling demand for nitrogen credits

The demand for N reduction credits on the part of point sources was derived from data on existing point sources and on the expected costs of alternative nitrogen reduction technologies. Data on nitrogen discharges from point sources that are contained in NPDES permits were available in a database developed by Gianessi and Peskin (1984). This database consists primarily of data from EPA's Permit Compliance System (PCS). These data report effluent volume and allowable pollutant concentrations for major NPDES discharge facilities (U.S. EPA, 1998). Gianessi and Peskin supplemented PCS data with information from other sources to develop county-level estimates of effluent flow and nitrogen loadings by municipal and industrial sources.[2] These data may overestimate existing point sources of N because of improvements in treatment that have occurred between the early 1980s and the present. On the other hand, population has increased, as well as total waste loads. We assumed the data represented a reasonably accurate picture of relative N loadings from point sources across the Mississippi drainage basin. These data also provide estimates of baseline N concentrations in point source discharges for each county.

Cost functions for different technological approaches for retrofitting existing municipal sewage treatment plants to reduce N discharges were adapted from cost equations developed originally by Hazen and Sawyer and Smith Associates (1988), as modified and reported in Camacho (1992) for the Chesapeake Bay Program. We assumed a technology requirement of activated sludge with nitrification technology (ASN). This technology reduces nitrate concentrations in effluent to 3 mg/l (Camacho, 1992). Equations for annualized capital and operation and maintenance costs of retrofitted plants, in 1990 constant dollars, were estimated as nonlinear equations of the form:

$$\text{Capital} = a(\text{Flow})^b$$

$$\text{O\&M} = c(\text{Flow})^d$$

where Capital—capital costs, O&M—annual operation and maintenance costs, Flow—design flow in million gallons per day (mgd), $a$, $b$, $c$, $d$—regression coefficients and exponents (Table 1).

A cost equation was estimated for each county of the Mississippi Basin for a hypothetical treatment plant with annual flow and N discharge equal to the total county point source discharge reported in Gianessi and Peskin. Treatment costs may be understated because the data were aggregated at the county level, resulting in larger plant sizes that garner economies of scale. This assumption would have the effect of reducing the average cost of treatment. Average annual county-level costs for the

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[2] Concentrated Animal Feeding Operations are considered point sources by EPA but are not included in this database.

Table 1
Coefficients in planning level cost equation for retrofitting sewage treatment plans to activated sludge with nitrification

| Coefficient | | | | |
|---|---|---|---|---|
| Design flow | *a* | *b* | *c* | *d* |
| 0.5–5.0 mgd | 4,392,274 | 0.61 | 113,815 | 0.670 |
| 5.9–30.0 mgd | 3,648,391 | 0.71 | 90,377 | 0.816 |

Capital=$a(\text{Flow})^b$.
O&M=$c(\text{Flow})^d$.
Assumes year-round N removal and phosphate ban in effect.
Source: Camacho (1992).

new technology ranged from $1.79 to $22,976.81 per pound of N reduced.

To represent the demand for nonpoint source nitrogen credits on the part of point sources within the USMP model, metacost functions were estimated for each USMP model subregion from the estimated county wastewater treatment costs (Fig. 2). These functions were estimated by arraying average county-level costs ($/lb N reduction) from high cost to low cost in each USMP region and fitting a function through the points. These metacost functions can be viewed as regional demand functions for nonpoint source N reductions; that is, the curve shows that the cost per unit N reduction the point sources in the subregion would incur by installing advanced treatment over a range of N reductions. Point sources should be indifferent between paying that cost for N reduction by retrofitting and compensating farmers for an equivalent amount of N reduction credits. Baseline N effluent concentrations and total point source N reduction that would result from installing advanced treatment are shown for each USMP subregion in the Mississippi Basin in Table 2. Without a trading program, point sources would have to spend $26.3 billion to meet more restrictive N discharge requirements and would reduce N discharges by 862.2 million pounds per year.

The metafunctions were incorporated into the objective function of the USMP model to capture the demand for N loss reduction credits that could be supplied to point sources. Farmers consider the value of these credits when making planting and crop management decisions. The model finds the most efficient combination of production practices for maximizing profits, including the sale of N reduction credits to point sources. The amount of credits sold

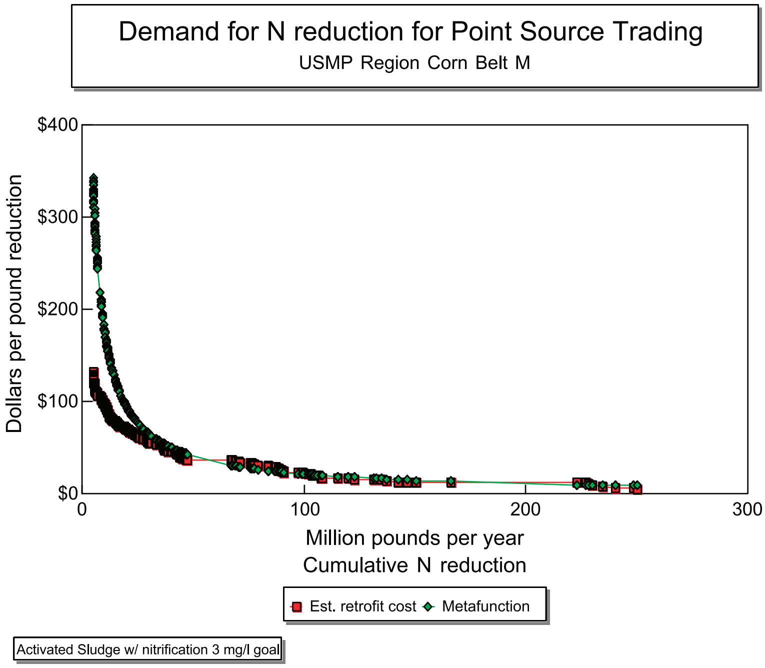

Fig. 2. Demand for N reduction for point source trading.

Table 2
Summary of point source control costs

| Region | Baseline effluent concentrations | Point source N reduction requirement | Weighted average treatment cost | Total abatement cost |
|---|---|---|---|---|
| | mg/l | Million pounds | $/pound | Million $ |
| NTN | 14.8 | 45.21 | 40.16 | 1815.6 |
| LAF | 28.1 | 1.78 | 35.97 | 64.0 |
| LAK | 14.6 | 41.14 | 40.69 | 1674.0 |
| LAM | 22.2 | 97.41 | 20.62 | 2008.6 |
| CBM | 19.7 | 250.41 | 29.85 | 7474.7 |
| CBN | 21.1 | 48.36 | 36.42 | 1761.3 |
| CBO | 30.8 | 1.50 | 48.94 | 73.4 |
| NPF | 30.5 | 5.84 | 48.17 | 281.3 |
| NPG | 24.8 | 3.49 | 64.64 | 225.6 |
| NPH | 29.6 | 15.20 | 39.44 | 599.5 |
| NPM | 27.8 | 27.37 | 24.59 | 673.0 |
| APN | 18.8 | 94.02 | 34.17 | 3212.7 |
| SEN | 27.3 | 29.99 | 34.92 | 1047.2 |
| DLN | 25.9 | 11.43 | 29.80 | 340.6 |
| DLO | 25.6 | 76.37 | 24.04 | 1835.9 |
| SPH | 18.6 | 9.40 | 41.64 | 391.4 |
| SPJ | 28.0 | 65.86 | 24.29 | 1599.7 |
| SPM | 22.8 | 6.74 | 29.82 | 201.0 |
| MNF | 25.0 | 1.57 | 53.03 | 83.2 |
| MNG | 21.8 | 27.68 | 30.26 | 837.6 |
| MNH | 23.4 | 1.41 | 61.69 | 87.0 |
| Total | | 862.18 | | 26287.3 |

within a region depends on the demand for N credits by point sources and the cost of reducing N losses in agriculture by altering production practices. Agriculture will supply N reduction credits up to the point where the marginal cost of producing the next N reduction credit is greater than the marginal cost of point source treatment or until the total regional point source demand is met. In other words, as one moves along the N reduction demand curve, agriculture will be willing to implement N reduction practices as long as the price offered by point sources is greater than the cost of supplying the next unit of N reduction.

## 5. Results

The price and amount of N reduction credits purchased by point sources in each region is reported in Table 3. Given the opportunity to purchase N reduction credits from agriculture within their respective regions, point sources would purchase 783.9 million pounds of N reduction per year or 91% of the total point source reductions obtainable by the required treatment technology. In 16 regions, point sources met their total responsibility by purchasing N reduction credits. In the other five regions, some point sources installed the advanced technology because it was cheaper than purchasing N reduction credits. It appears from the model results that farmers produced most of the nitrogen reduction credits by reducing nitrogen fertilizer use. Nitrogen fertilizer use declined in the Mississippi Basin by 11%. There were only minor changes in tillage practices and in the mix of crops grown within the Basin.

Point sources paid a total of $12.0 billion for N loss reduction credits to farmers and realized a benefit of $18.9 billion by not having to install advanced treatment. This is calculated by taking the integral under the metacost function for each USMP region between the maximum observed baseline treatment

Table 3
Summary regional demand for credits, N credits purchased, and the cost of a marginal credit

| Region | Point source N reduction requirement | Pounds N traded | Cost of marginal trade |
|---|---|---|---|
| | Million pounds | Million pounds | $/lb |
| NTN | 45.21 | 11.20 | 40.99 |
| LAF | 1.78 | 1.78 | 20.75 |
| LAK | 41.14 | 41.14 | 15.67 |
| LAM | 97.41 | 89.50 | 12.05 |
| CBM | 250.41 | 250.41 | 9.48 |
| CBN | 48.36 | 29.45 | 27.53 |
| CBO | 1.50 | 1.50 | 35.12 |
| NPF | 5.84 | 5.84 | 31.18 |
| NPG | 3.49 | 3.49 | 44.08 |
| NPH | 15.20 | 15.20 | 29.06 |
| NPM | 27.37 | 27.37 | 18.34 |
| APN | 94.02 | 94.02 | 20.72 |
| SEN | 29.99 | 21.44 | 16.78 |
| DLN | 11.43 | 2.44 | 36.99 |
| DLO | 76.37 | 76.37 | 10.50 |
| SPH | 9.40 | 9.40 | 25.46 |
| SPJ | 65.86 | 65.86 | 15.25 |
| SPM | 6.74 | 6.74 | 19.80 |
| MNF | 1.57 | 1.57 | 26.69 |
| MNG | 27.68 | 27.68 | 21.94 |
| MNH | 1.41 | 1.41 | 38.14 |
| Total | 862.18 | | |

cost (in dollars per pound N reduced) and the treatment cost at which the marginal "trade" took place. Overall, there was a net welfare gain to society of $45.6 billion from allowing trades, including changes in consumer and producer surpluses.

The ability of farmers in the Mississippi Basin to sell N reduction credits to point sources has implications for the agriculture sector in the Basin and the rest of the country. Farmers in the basin adjust production practices in response to, not only commodity prices, but also to the price of nitrogen credits. Farmers outside the basin respond only to commodity prices. The impact on commodity prices is small (less than 1% for most crops). Within the Basin, acreage planted to most crops increases slightly (1.2% for all cropland), while there are small reductions in acreage planted outside the regions (0.5%). Total acreage planted in the US increases by about 0.8% in response to price changes.

In the Mississippi drainage basin, N losses are reduced by 5.9%. In the rest of the country, N losses decrease slightly as a result of price-induced shifts in production. Changes in production practices in the Mississippi Basin produced a 6% increase in soil erosion primarily due to an increase in moldboard plowing. Erosion decreases slightly outside the basin. Net changes in soil erosion resulted in an estimated $23.1 million increase in sediment damages to water uses. Changes in crops and management practices result in a 1.2% decrease in phosphorus losses in the basin and a slight decrease outside the Basin.

## 6. Conclusions

This analysis demonstrates some of the economic benefits of allowing point sources to purchase nitrogen reduction credits from agricultural sources of nitrogen in the Mississippi Basin. Allowing trades between point sources and agriculture reduced overall N abatement costs. Point sources in most regions benefited by being able to purchase N reduction credits from agriculture. The degree to which point sources and society benefit from a credit trading program would depend greatly on the structure of the "market" that is created. Possibilities include bilateral negotiations between individual point sources and individual farmers and water-quality clearinghouses where the State buys credits from farmers and sells them to point sources (Woodward and Kaiser, 2002). Some of the welfare gains from trading would be lost to transactions costs in establishing credit markets, such as scoring each farmer's credits and monitoring implementation of BMPs. These costs could be quite high.

Some of the benefits to the Gulf of Mexico from reduced nitrogen loads might be offset by increased sediment loads in rivers and lakes in the basin. These results highlight the need to carefully consider all the implications from a policy, particularly from a policy targeted at a particular region or for a single pollutant.

The results indicate that there are wide differences in the cost of N reduction between regions. This implies that further gains could be made by allowing trades between regions. However, different trading ratios between regions would have to be set to account for differences in the marginal impacts that N from each region has on the Gulf.

This work can be extended to examine how different trading ratios affect the magnitude of trading. We assumed that point sources could meet their discharge obligations by purchasing credits on a one-to-one basis. An efficient trading ratio depends on the variance of nonpoint source loads and the expected damages to water users, relative to point source loads, and may be greater than one or less than one (Horan et al.). Requiring point sources to purchase more than one nonpoint source credit for each unit of point source discharge would increase the cost of trades to point sources, decreasing demand for N credits. However, the amount of crop acreage under a nutrient management plan for the purpose of supplying credits may actually increase. The greater the amount of cropland supplying nitrogen reduction credits, the greater the potential impact on commodity prices and the consumers of agricultural products.

Finally, this analysis required all point sources to install advanced nitrogen treatment. Addressing the Gulf's hypoxia problem probably requires something less stringent than this. However, the results do demonstrate that, in many areas, it would be advantageous to allow trading when local or regional water quality needs require reductions in nitrogen and when nonpoint sources do not face regulations.

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