Nitrogen Sources and Gulf Hypoxia: Potential for Point-Nonpoint Trading

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A zone of hypoxic (<2.0 mg/l of dissolved oxygen) and anoxic (0.0 mg/l of dissolved oxygen) waters has become a dominant feature of the northern Gulf of Mexico. Hypoxia is defined as a deficiency in breathable oxygen sufficient to cause damage to living tissue. Anoxia is a deficiency in oxygen sufficient to cause death. Analyses of sediment cores from the Louisiana Shelf indicate that the increased eutrophication and hypoxia seen in the northern Gulf of Mexico are the result of increased nitrogen loadings from the Mississippi River (Rabalais et al., 1996). This paper uses the USMP model to explore point-nonpoint trading as a potential policy tool for reducing nitrogen loads entering the Gulf via the Mississippi River.

The Gulf of Mexico contains almost half of the nation's coastal wetlands and supports approximately 40 percent of its fishery landings. Hypoxic conditions can kill benthic marine organisms, possibly affecting the productivity of coastal waters and impacting commercial and recreational fisheries. Nutrient concentrations in the Mississippi River have increased dramatically in this century and have accelerated since 1950, coincident with increasing fertilizer use on cropland in the Midwest (Goolsby and Battaglin, 1995). 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. Nonpoint source pollution from agriculture is estimated to contribute more than 80 percent of the nitrogen loadings in the Mississippi basin (Battaglin, Kendall, Goolsby, and Boyer, 1997). The appropriate mix of policy tools to most efficiently reduce loads to the Gulf depends on the costs of controlling pollution from different sources and the benefits of control.

This paper focuses on the costs of controlling nitrogen (N) from two sources in the Mississippi Basin, crop agriculture and point sources. A variety of policy tools are available for reducing loadings of pollutants in general, and nitrogen in particular. Point source discharges, defined as pollution entering waterways through a pipe or a ditch, are subject to national regulatory policies that place requirements on pollution control technology (design standards), or on the quality of effluent (performance standards). Discharges are regulated at the outlet through permits of the National Point Discharge Elimination System.

All point sources are subject to these permits. The primary source of point source N in the Basin is municipal sewage treatment plants.

Nonpoint source pollution, defined as pollution carried over and through the ground by rainfall and snowmelt, is not regulated at the federal level. Agriculture is the largest source of nonpoint source pollution (EPA, 1995b). A mandate for control was passed to the states by Section 319 of the Clean Water Act. States are not restricted in the control mechanisms to be used, and most have opted for voluntary approaches that rely primarily on education, technical assistance, and financial incentives. In recent years more restrictive controls have started to appear, most requiring the development and implementation of farm plans that use best management practices.

For this analysis we assume a policy of requiring all point sources discharging N in the Mississippi basin to install advanced nutrient removal technology. Such a policy would be the easiest to implement given current water quality laws, where only point sources of pollution are controlled through command and control policies. We impose what we think to be a fairly stringent requirement that all treatment plants achieve a discharge level of 3 mg/l. At the current time the amount nitrogen reduction required to address the hypoxia problem is unknown.

An alternative to reducing only point sources is to reduce nonpoint sources, either in combination with point sources or alone. If the cost of reducing a unit of N is less for nonpoint sources, then efficiency considerations would suggest that reductions are targeted to these sectors first. A way to do this is under current water quality laws is through a trading system. Simply, trading allows point sources to “purchase” required reductions from cheaper sources as a means of meeting their discharge requirements. Suppose a point source is required to reduce its N loadings by 50 percent, and that this costs the firm $150 per pound of N reduced. Also suppose that improved nutrient management practices on cropland in the same basin could produce the same reduction in N loads for only $20 per pound. Efficiency is gained if the point source can pay the nonpoint source to install nutrient management practices rather than installing the more expensive treatment technology; an equivalent reduction in N discharge can be achieved at a lower cost to society. Such a system is being used in some basins in North Carolina (EPA).

There are a number of conditions necessary for a trading program to be successful (Bartfeld, 1993):

***Location* -** Both point and nonpoint sources must be in the same basin, where they would be contributing pollutants to the same water bodies. Trading is also best suited for water bodies with long pollutant residence times, and for water bodies where pollutant loads are less subject to fluctuations in weather. Large lakes and estuaries are therefore more likely candidates than rivers.

***Sources* -** Both point and nonpoint sources must contribute significantly to total pollutant loads, and the contributions must be quantified. If the nonpoint source contributions are very large in relation to the point source contributions, then the point sources will be unable to purchase enough reduction to make much difference in water quality. Required point source reductions are limited by the initial loads. On the other hand, if point sources are very large in relation to the nonpoint sources, they will be unable to trade as much they would like.

***Relative Control Costs* -** The costs of reducing loadings from nonpoint sources must be less than the costs of reducing point source loadings, and possibly much less. All currently proposed trading programs require point sources to purchase more than one unit of reduction from nonpoint sources for every unit reduction to which they are obligated. The reason is that nonpoint source reductions are highly uncertain, and trading ratios in excess of 1:1 are used to account for this uncertainty (Malik, Letson, and Crutchfield, 1993). The upshot of this is that, for a trading ratio of 3:1, the marginal cost of nonpoint source reduction must be less than one-third the marginal cost of point source reduction before point sources would benefit by trading.

***Type of Pollutant* -** Conservative pollutants are most likely candidates for trading. Conservative pollutants are those that degrade slowly, and whose impacts are felt through total accumulation. Timing and location of discharge are relatively unimportant.

The N problem in the Mississippi basin meets these conditions. Nitrogen is a conservative compound generated by both point and nonpoint sources, and nitrogen has a long residence time in the Gulf. There are numerous sources of both point and nonpoint sources. The only questions to be addressed are whether point source abatement costs are greater than nonpoint source abatement costs, and whether nonpoint source loads are sufficient to meet the point source reduction requirements we have imposed.

To affect trading between point sources and agriculture, we create a market for N reduction credits that are supplied by agriculture and purchased by point sources. We assume that point sources can only trade with nonpoint sources (no point-point or nonpoint-nonpoint trading), that trades can only occur between sources within a region (defined here by the regions in the agricultural sector model), and that a trading ratio of 1 to 1 is established. These assumptions will be relaxed in future extensions.

Method for estimating point source N reduction costs

Estimating costs for reducing N loadings from present levels requires data on the characteristics of existing point sources and information on the expected costs of alternative reduction technologies. While nonpoint discharges are regulated under the National Pollution Discharge Elimination Program (NPDES), data from permits issued under NPDES available in the Permit Compliance System (PCS) data base suffer from several flaws. First, not all point sources for which permits are required are contained in the database. Monitoring data is primarily focused on "major" NPDES discharge facilities. Major is defined by EPA as facilities which discharge more than one million gallons per day, or are considered to have a significant environmental impact on the area into which their discharge is located (USEPA, 1998). Missing sources appeared to be particular problems in Missouri, Nebraska, Minnesota, and Wisconsin (USEPA, 1995; USDA-ERS, 1997 fig. 2.2.3). Second, for stream reaches where N is not a critical factor in water quality, NPDES permits do not place conditions on N discharges and, therefore, no information on N discharges is available. To avoid these problems, an older database developed by Gianessi and Peskin (1984) that estimates N sources was used. Data on effluent flow, TKN, and other pollutant loadings by municipal and industrial sources, by county for the early 1980's was available. Flows and loadings from industrial sources were added together, assuming that industrial sources would contribute their loadings to any new or enhanced municipal treatment sewerage plant.

These data may overestimate existing point sources of N because of improvements in treatment that have occurred between the early 1980's and the present. Costs may be understated because the data were aggregated for each county, resulting in larger plant sizes that garner economies of scale. Nevertheless, the data are believed to represent an accurate picture of relative N loadings from point sources across the Mississippi drainage basin. Specifically, these data show where the largest amounts of point source N discharge are located relative to agricultural land that could engage in N reduction trading.

Information on the costs of different methods for modifying existing municipal sewerage treatment plants to accomplish increased N reduction was 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. The retrofit planning cost curves provide estimates for four types of secondary N treatment to accomplish biological N removal: extended aeration (EA), activated sludge (AS), activated sludge with nitrification (ASN), and activated sludge with fixed film (ASF). Curves were estimated for two levels of TN removal (8.0 mg/l and 3.0 mg/l seasonal), for two levels of discharge range (0.5 to 5.0 mgd and 5.0 to 30 mgd), and for areas with and without bans on phosphate discharges. Equations for annualized capital and operation and maintenance costs, in 1990 constant dollars, were estimated as nonlinear equations of the form:

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

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

where Capital = capital costs

O&M = operation and maintenance costs

Flow = design flow in million gallons per day (mgd)

a,b,c,d = regression coefficients and exponents.

These cost curves generally drop rapidly from negligible discharges to 5 mgd, then remain relatively flat but decreasing over the range from 5 to 30 mgd (see figure 1). For this paper, we assume that all municipal sewage treatment plants must install activated sludge with nitrification, so that an N discharge target of 3 mg/l is met.

The cost equations were evaluated for a hypothetical plant with flow and N discharge equal to the total municipal and industrial discharge in each county. The total capital and O&M cost of the retrofit was then divided by the difference in N discharge between the base condition and the 3.0 mg/l level, to calculate an annual cost per pound of N reduction. Costs ranged from $1.79 to $22,976.81 per pound of N removal per year.

Modeling nitrogen credit from agriculture

The supply of N credits from agriculture were estimated for each region within the USMP regional agricultural model. The model is used to estimate price and quantity impacts to the agriculture sector in response to the creation of a market for N reductions. The USMP modeling system comprises a mathematical programming model of the major crop and livestock product markets, crop activities based on crop yields, erosion rates, and nutrient losses generated through USDA's EPIC simulator, and a GIS incorporating planted acres from the 1992 National Resource Inventory.

Prices and quantities of agricultural commodities and inputs are solved for by the model, consistent with a free-market equilibrium as influenced by voluntary commodity programs and constrained by government regulations (House). The model includes the major livestock and poultry enterprises and the ten major field crops. For each "baseline" solution or alternative scenario, the model tallies associated levels of selected agricultural environmental indicators and acreage under various rotation systems and tillage practices, at the national level, as well as for 10 farm production regions, and 45 model regions[1]. The demand and supply functions for commodities are consistent with those used in FAPSIM (Salathe, et al.), USDA's econometric model of the agricultural sector.

The crop subsector is modeled through the use of cost of production (COP) budgets for crop rotation and tillage systems in the 45 regions as sampled through the National Resource Inventory (NRI) and the Cropping Practice Survey (CPS). Crop rotations include continuous planting, two-year, three-year and four-year rotations that can include hay and fallow activities. Tillage practices represented include conventional tillage, with and without moldboard, no-till, mulch-till, and ridge-till. Acreage adjustment among the alternative production activities is specified by constant elasticity of transformation functions.

The EPIC biophysical model was used to simulate a set of crop rotation and tillage systems for each region, generating a vector of inputs and outputs for each system (Williams, et al.) The inputs include specific fertilizer applications and the outputs include crop yields, environmental losses of chemicals and erosion. The initial fertilizer application was set to be consistent with agronomic practices for the region. Changes in yield and N losses were estimated by running each of the cropping systems represented in USMP through the EPIC biophysical model for sixty years after reducing N application rates by 10-, 20-, 30- and 40-percent. The results from the EPIC simulations were used to construct four sets of reduced N enterprises for each of the base activities, increasing the total number of crop production activities represented in the model to about 2,400. The expanded set of production activities was then added to the model and used to approximate the nonlinear relationships between N application rates, yields, and N losses. N losses are the difference between N available to crops and the amount taken up. A farm can supply N credits by reducing N losses.

Convexity constraints and risk premiums were used to add the reduced N production activities to the model. The convexity constraints permit convex combinations of production activities with respect to N application rates to be formed, thereby allowing the reduction in application rates per cropping system to vary from zero to forty percent and changing the implicitly defined production functions associated with each rotation-tillage system from fixed proportion to varying proportion. In addition, a risk premium[2] was charged for the reduced nitrogen activities, reflecting the cost, born by farmers, of the censoring of the upper tail of the yield distribution and the consequent increase in revenue risk. This charge is consistent with reported fertilizer data, the underlying data used in USMP and with evidence that farmers use fertilizer as a substitute for revenue insurance (USDA, 1994; Babcock and Hennessy; and Smith and Goodwin).

In order to represent the demand for nonpoint reductions in N on the part of point sources within the USMP model, meta-cost functions were estimated for each USMP model subregion (intersection of Land Resource Region and Farm Production Region) from the estimated county wastewater treatment costs (figure 2). Figure 3 shows the USMP regions. These meta-cost functions can be viewed as demand functions for point-nonpoint source N reduction trading. That is, the curve shows the cost point sources in the subregion need to incur in order to achieve a given cumulative reduction in N discharge. Point sources should be indifferent to paying that cost for N reduction by retrofitting, or compensating farmers for nonpoint source reductions in N of equivalent size. Average N effluent concentrations, and average reatment costs weighted by the relative N discharge in each county, are shown for each subregion in table 1. The ability for farmers to sell N loss reductions to point sources places a value on N losses. In a sense, an externality has been internalized, and farmers consider the value of reducing N losses when making planting decisions.

Given the demand for nitrogen reductions, the agriculture sector in each region can supply N reduction credits by changing fertilizer application rates, switching production practices, or growing different crops. The amount of credits sold within a region depends on the demand for N credits and the costs of reducing N losses in agriculture. Agriculture will supply N credits up to the point where the marginal cost of producing the next credit is greater than the marginal cost of treatment, or until the total point source demand is met.

The price of the marginal sale of N credits in each region is reported in table 1, as well as the amount of N credits purchased by the point sources. The results are reported for each of the 21 USMP regions that are in the Gulf of Mexico drainage area. Given the opportunity to purchase N reduction credits from agriculture within their respective regions, point sources would pay agriculture to reduce N loads by 407.93 million pounds, or 47 percent of total point source reductions obtainable by the required technology. In 12 regions, point sources can meet their total responsibility by buying credits. In the other nine, agriculture could not meet the entire demand because point sources could meet at least part of their obligation more cheaply by installing the advanced treatment technology. However, credits were purchased in all regions.

In most regions, the marginal "price" of the last nitrogen credit was less than the average weighted cost. In some regions the price was higher, indicating that the cost of supplying credits was high, and only those plants facing the highest marginal treatment costs purchased N credits. Point sources realize cost savings of about $14 billion by not having to install advanced treatment and instead purchasing N reductions from agriculture.

The ability of farmers in the Mississippi Basin to sell N reduction credits to point sources has important implications for agriculture in the Basin and the rest of the country. Table 2 summarizes the changes in crop prices, acres planted, and farm income in the Mississippi drainage and rest of the U.S. The prices of most commodities increase. Only the prices of hay and silage decrease. Within the Basin corn, soybean, wheat, and rice are shifted into other crops, primarily oats, silage, and hay. Elsewhere in the U.S., the acreage planted to all crops except soybeans and hay increases. The most sizable increases were for wheat and rice. Total acreage planted increases in the Mississippi Basin and decreases in the rest of the country. Total acreage planted in the U.S. increases by about 0.8 percent. Net cash returns for crop production in the entire U.S. increase by about 1 percent ($465 million).

The changes in crop production have implications for environmental quality (table 3). In the Mississippi drainage, N losses are reduced, as might be expected. In the rest of the country, where N loss is still an unpriced externality, N losses increase as the rise in the prices of some major crops spurs increased production and increased fertilizer use. Changes in production practices in the Mississippi Basin results in a small increase in soil erosion, primarily from an increase in moldboard plowing. The increase in erosion could have negative consequences for water quality in the Basin. Changes in crops and management practices also result in an increase in phosphorus losses in the basin, and virtually no change outside the Basin. The consequences of changes in erosion and phosphorus losses would need to be considered in a complete benefit-cost assessment of a trading program.

Conclusions

The analysis presented above demonstrates some of the economic benefits of allowing point sources to purchase nitrogen reduction credits from agricultural sources of nitrogen in the Mississippi Basin. Creating a market for N reduction credits reduced overall N abatement costs. Some of the benefits to the Gulf might be offset by reduced water quality due to sediment, and increased nitrogen loadings elsewhere. These results highlight the need to consider carefully all the implications from a particular policy.

This analysis also highlights the utility of the USMP for assessing nutrient trading policies. The use of sector model allows for a market for nutrient credits to be created, and tracks the agronomic impacts both within and without the geographic boundaries of the market.

This analysis is preliminary in three respects. First, the level of nitrogen reductions needed in the Mississippi basin to reduce the hypoxia problem has yet to be determined. In our analysis, we based a level of nitrogen control on a policy of installing advanced treatment at all point sources. This may be much more than is economically justified given the amount of N reduction needed to reduce the hypoxic zone and the benefits of doing so. A lower nitrogen reduction target would reduce overall control costs. Estimates of the economic benefits to commercial and recreational uses of the Gulf will to a large degree determine the level of nitrogen control that is most efficient.

Second, inter-basin trading that accounts for differences in control costs between regions would result in a more efficient allocation of nitrogen abatement between sources and between regions. As seen in table 1, there is a wide variation in the cost of nitrogen reduction credit between regions. The large differences in the price of a credit between regions indicate the potential for increased efficiency by allowing interregional trades.

Finally, we assumed that point sources could meet their discharge obligations by purchasing credits on a 1 to 1 basis. Uncertainty about the ability of nonpoint sources to actually reduce nitrogen loads requires that more than one credit be purchased to meet a unit reduction goal. Trading ratios of 2:1 or 3:1 would increase the cost to point sources of a trade, and reduce trading activity. Future analyses will examine these issues.

Table 1 - Summary of point source control costs, total demand for credits, amounts purchased, and the cost of a marginal credit.

Region	Effluent conc.	Total point source N reduction requirement	Weighted average treatment cost	Pounds N traded	Cost of marginal credit
	- mg/l -	-million pounds-	$/pound	-million pounds-	$/pound
NTN	14.8	45.21	40.16	1.27	98.83
LAF	28.1	1.78	35.97	1.78	20.75
LAK	14.6	41.14	40.69	41.14	15.67
LAM	22.2	97.41	20.62	97.41	11.55
CBM	19.7	250.41	29.85	135.21	16.62
CBN	21.1	48.36	36.42	10.55	45.99
CBO	30.8	1.50	48.94	1.50	35.12
NPF	30.5	5.84	48.17	5.84	31.18
NPG	24.8	3.49	64.64	3.49	44.08
NPH	29.6	15.20	39.44	15.20	29.06
NPM	27.8	27.37	24.59	27.37	18.34
APN	18.8	94.02	34.17	1.29	187.97
STN	27.3	29.99	34.92	3.16	61.46
DLN	25.9	11.43	29.80	3.36	31.66
DLO	25.6	76.37	24.04	8.38	41.92
SPH	18.6	9.40	41.64	9.40	25.46
SPJ	28.0	65.86	24.29	4.69	53.31
SPM	22.8	6.74	29.82	6.23	20.56
MNF	25.0	1.57	53.03	1.57	26.69
MNG	21.8	27.68	30.26	27.68	21.94
MNH	23.4	1.41	61.69	1.41	38.14
Total		862.18		407.93	

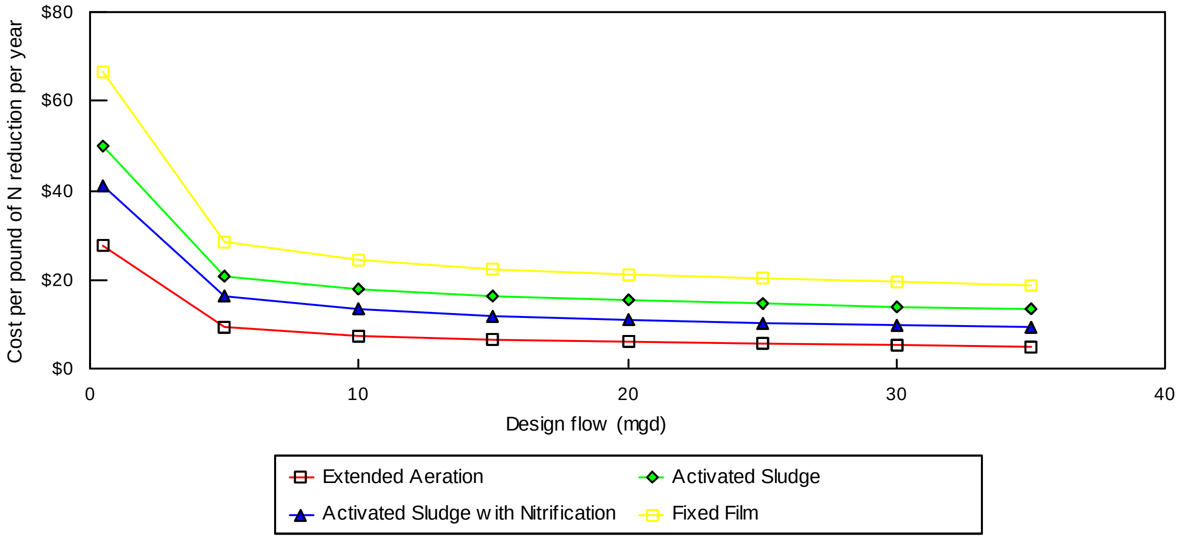
Table 2 - Changes in crop prices and acreage planted, by Mississippi drainage and rest of U.S.

Crop	Price change	Change in acreage planted - Miss. Basin	Change in acreage planted - rest of U.S.
		- percent -	
Corn	2.4	-0.3	0.6
Sorghum	1.6	1.3	0.0
Barley	0.4	0.0	0.0
Oats	4.2	6.4	0.0
Wheat	0.5	-0.3	5.4
Rice	3.0	-5.3	6.7
Soybeans	0.9	-0.7	-0.8
Cotton	0.6	0.6	1.9
Silage	-0.1	2.5	0.0
Hay	-1.5	8.0	-0.8
Total		1.1	-0.1

Table 3 - Changes physical environmental indicators, by Mississippi drainage and rest of U.S.

Indicator	Mississippi Basin	Rest of U.S
	-percent-	
Nitrogen loss	-0.8	0.2
Phosphate loss	0.5	0.0
Soil erosion	0.9	0.0

Fig. 1--Planning level Biological Nitrogen Removal Retrofit Cost Curves



Reduction from 50 to 3 mg/l concentration

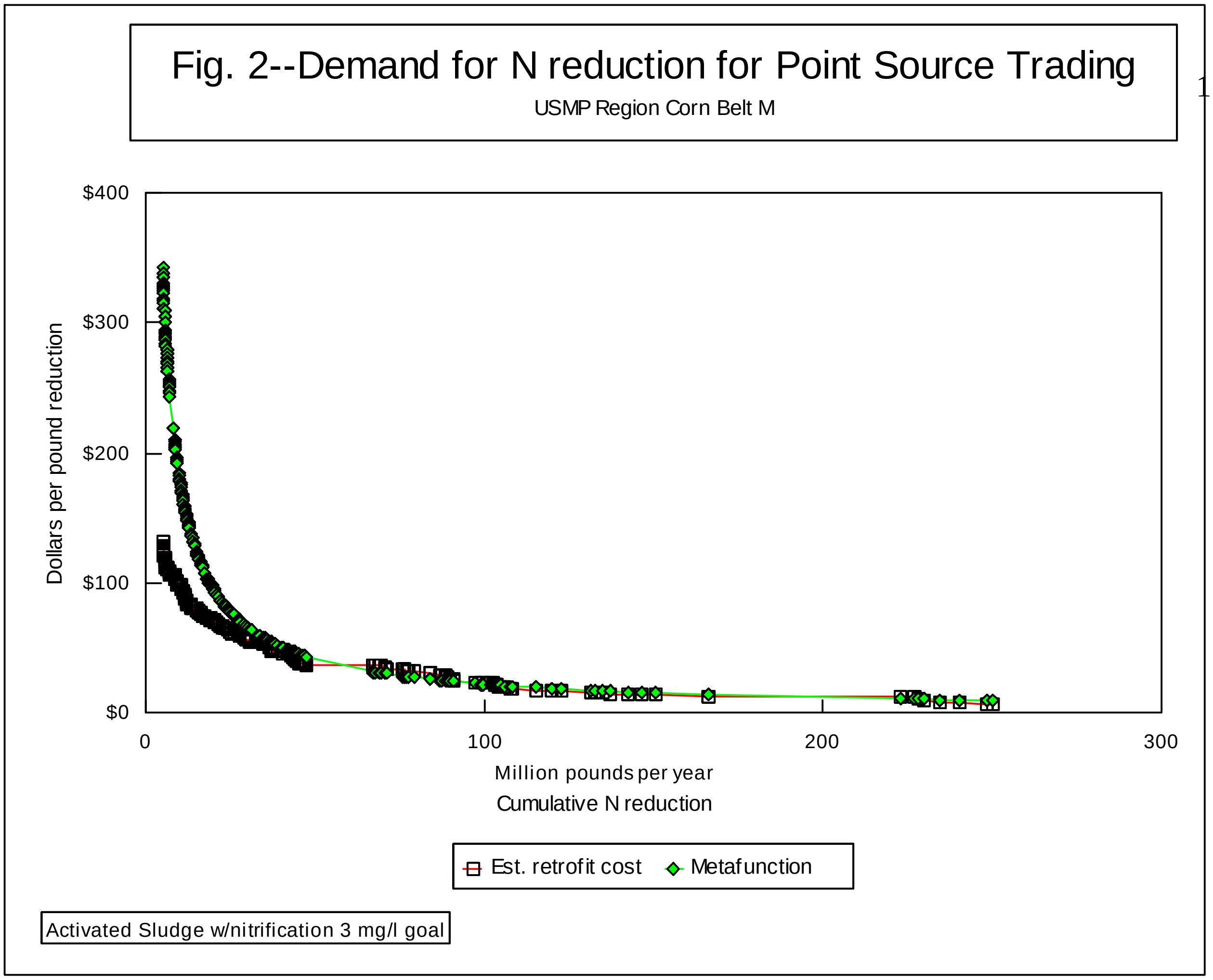
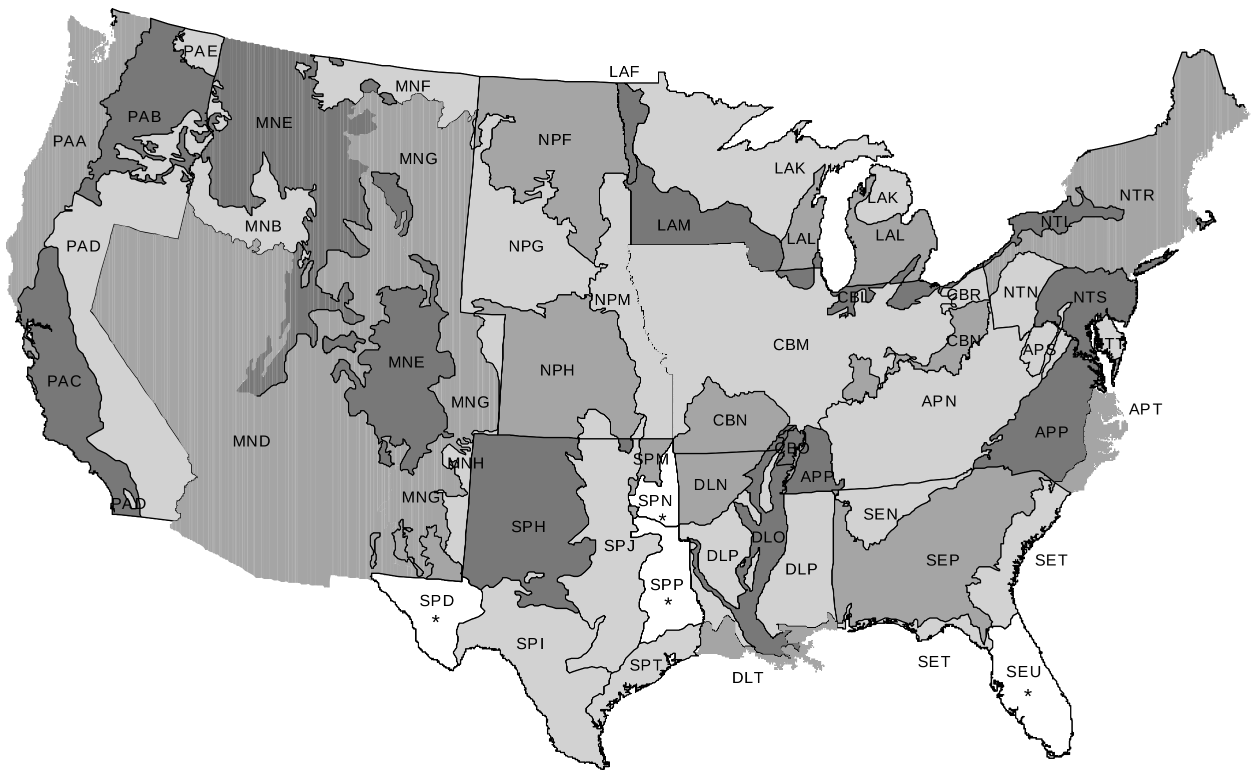


Fig. 2--Demand for N reduction for Point Source Trading
USMP Region Corn Belt M
Dollars per pound reduction
$400
$300
$200
$100
$0
0
100
200
300
Million pounds per year
Cumulative N reduction
Est. retrofit cost
Metafunction
Activated Sludge w/nitrification 3 mg/l goal

USMP Regions



* Data not available for SPD. SPP. SPN. and SEU.

Figure 3

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1. The 45 regions were selected by overlaying the National Agricultural Statistical Service's 10 farm production regions on the 20 land resource regions developed by the Natural Resources Conservation Service.

2.The risk premium was calculated according to the following functional relationship:

$$R_{i,k} = \begin{cases} 0 & if\ NR_{i,k} \leq NR_{b,k} \\ 2(NR_{i,k} - NR_{b,k}) & if\ NR_{i,k} \geq NR_{b,k} \\ R_{j,k} & if\ NR_{j,k} \geq NR_{i,k} \geq NR_{b,k};\ i \geq j \end{cases}$$

where *b* represents the base nitrogen application rate, *(i,j)* = 1,2,3,4 represents the percentage reduction from lowest to highest in nitrogen applied from base level, $R_{i,k}$ represents the risk premium associated with fertilizer application rate *i* for production system *k*, and $NR_{i,k}$ represents net return associated with nitrogen application rate *i* for production system *k*.