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# Reducing Nitrogen Runoff from the Upper Mississippi River Basin to Control Hypoxia in the Gulf of Mexico: Easements or Taxes?

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**Abstract** *This paper integrates economic and physical models to estimate the social cost of reducing nitrogen loads from the Upper Mississippi River Basin to the Gulf of Mexico under three conservation easement policies and a fertilizer-use tax. The economic models predict farmers' choice of crops and management practices at more than 44,000 Natural Resource Inventory sites in the basin. The physical model assesses the impact of land use changes on nitrate-N concentrations in the Mississippi River. Results suggest that the fertilizer-use tax is much more cost effective than the three easement policies. Incentive payments for conservation tillage are most cost effective among the three easement policies, but can reduce nitrate-N concentrations by only 37%. The potential for incentive payments for corn-soybean rotations is even more limited. Payments for cropland retirement can be used to achieve the largest reduction in nitrate-N concentrations, but are least cost effective among the four policies considered in this paper.*

**Key words** Fertilizer-use taxes, conservation easements, hypoxia, land use changes, nitrate water pollution, nonpoint source pollution, SWAT.

JEL Classification Codes Q24, Q25, Q28.

## Introduction

Human activity on land, in coastal areas, and further inland, is a major threat to the health, productivity, and biodiversity of the marine environment in the United States and throughout the world (Intergovernmental Conference 1995). In the northern Gulf of Mexico, nutrient loading from the Mississippi River Basin contributes to a high level of phytoplankton production in the spring (Brezonik *et al*. 1999). When the phytoplankton die and sink to the bottom, they are consumed by oxygen-using bacteria. This process of decay depletes the bottom waters of oxygen off the coast of Louisiana during the summer, resulting in a condition known as hypoxia. The hypoxic zone, or "Dead Zone," covering up to over 7,000 square miles of the Gulf of Mexico, has become a serious threat to commercial fishing, shrimping, and recreation industries. The livelihoods of many thousands of people and their communities

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are at risk, as is the large marine ecosystem on which they depend (National Center for Appropriate Technologies 2005). The Upper Mississippi River Basin (UMRB) is under increasing scrutiny as a major source of $NO_3$-N loadings to the Mississippi River, causing hypoxia in the Gulf of Mexico. The UMRB comprises only 15% of the drainage area of the entire MRB, but contributes more than half of $NO_3$-N loadings to the Gulf of Mexico (Goolsby and Battaglin 1997).

Numerous federal and state incentive-based programs have been initiated with goals of reducing the environmental impact of agricultural production, including the Conservation Reserve Program (CRP) and the Environmental Quality Incentive Program (EQIP). The 2002 Conservation Security Act expands these existing programs and includes provisions for new programs. *Ex ante* analysis of the cost effectiveness and environmental efficacy of changes in these programs, or *ex post* assessment of the outcomes of these programs, requires an integrated modeling framework capable of estimating both the economic and environmental impacts of land use changes on spatially heterogeneous land (Wu *et al*. 2004). It is also important to employ micro-level data in policy analysis both to achieve consistency with the underlying economic theory on which land use choice models are based, and to accurately capture the significant spatial variability in economic and environmental variables (Antle and Capalbo 2001; Hochman and Zilberman 1978).

The primary objective of this paper is to develop an empirical framework to estimate the social cost of reducing $NO_3$-N loads from the UMRB to the Gulf of Mexico under a fertilizer-use tax and three conservation easement policies (payments for conservation tillage, corn-soybean rotation, and cropland retirement). This objective is achieved by integrating a set of econometric models and a physical model (The Soil and Water Assessment Tool [SWAT]). The econometric models predict farmers' choice of crops, crop rotations, tillage practices, and participation in the CRP at more than 44,000 Natural Resource Inventory (NRI) sites in the UMRB under each policy. SWAT then simulates the level of $NO_3$-N concentrations in the Mississippi River based on the predicted changes in land use and farming practices in the UMRB. This integrated framework allows region-scale policy simulations while incorporating site-specific economic behavior and physical characteristics.

Our empirical results show that a fertilizer-use tax is more cost-effective than the three conservation easement policies for reducing $NO_3$-N concentrations in the Mississippi River. However, it is more difficult politically to institute the fertilizer-use tax than to implement the conservation easement policies. Among the three conservation easement policies, incentive payments for conservation tillage are most cost effective, but can reduce nitrate-N concentrations by only 37%. The potential for incentive payments for corn-soybean rotations is even more limited as an instrument for reducing $NO_3$-N concentrations. Payments for cropland retirement can be used to achieve the largest reduction in $NO_3$-N concentrations, but are the least cost effective among the four policies considered in this study.

## Literature Review

Much research has focused on the impact of farming practices on nitrate water pollution at the field, farm, or watershed levels (*e.g.*, De Roo 1980; Pionke and Urban 1985; Hallberg 1989; Gilliam and Hoyt 1987; Grady 1989). These studies have linked nitrate water pollution to land use, nitrogen application rates, crop management practices, and hydrologic settings. These studies, however, have not examined how the decisions that led to those cropping patterns and farming practices were made. Thus, they cannot be used to assess the efficiency of alternative policies for controlling nitrate water pollution.

The design of policy to encourage adoption of environmentally friendly farming practices requires analysis of adoption decisions. In response, many studies examine factors affecting adoption of crop management practices, such as conservation tillage (Ervin and Ervin 1982; Williams, Llewelyn, and Barnaby 1990; Helms, Bailey, and Glover 1987; Kurkalova, Kling, and Zhao 2003; Yiridoe and Weersink 1998), irrigation technologies (Caswell and Zilberman 1985), water quality protection practices (Fuglie and Bosch 1995; Cooper and Keim 1996), and adoption of conservation programs (Cooper and Osborn 1998; Bockstael *et al*. 1995; Parks and Schorr 1997; Johnson, Misra, and Ervin 1997). For example, Cooper and Keim use survey data to estimate payment levels needed to induce farmers to adopt alternative water quality protection practices.

Other policy instruments proposed for controlling agricultural pollution include input taxes, input regulations, ambient taxes, random fines, direct revelation, and type-specific contracts (Griffin and Bromley 1982; Shortle and Dunn 1986; Segerson 1988, Xepapadeas 1992; Cabe and Herriges 1992). Instruments that provide flexible incentives (such as ambient taxes) can be used to induce first-best control of nonpoint pollution, but information about farm-level characteristics is needed to design these first-best policy instruments. They have thus been criticized for high information and/or transactions costs (Cabe and Herriges 1992; Batie and Ervin 1999). This has led some to suggest the use of second-best policy instruments for controlling nonpoint pollution (Helfand and House 1995; Wu and Babcock 1996).

A number of empirical studies have modeled the interaction between agricultural production and water quality. These studies can be classified into disaggregate models and aggregate models. The disaggregated models are site-specific and model micro-unit decisions and their impact on water quality at the farm or watershed levels (*e.g.*, Braden *et al*. 1989; Johnson, Adams, and Perry 1991; Taylor, Adams, and Miller 1992). The aggregate models can be further classified into two groups. One group integrates an aggregate economic model (usually a regional or national linear programming model) with a physical model to analyze the impact agricultural practices and policies on water quality (*e.g.*, Piper, Huang, and Ribaudo 1989; Mapp *et al*. 1994). The aggregate economic model predicts the impact of alternative policies on land allocation and input uses, and the physical model estimates the impact of crop production on water quality. The second group of aggregate models examines policy impacts at the regional or national level while incorporating site-specific land characteristics (*e.g.*, Wu and Segerson 1995; Antle and Capalbo 2001; Wu *et al*. 2004). This study belongs to the second group. Specifically, it extends Wu *et al*. (2004) in two important aspects. First, this study compares the relative efficiency of a fertilizer-use tax and three conservation easement policies for controlling nitrate water pollution and hypoxia in the Gulf of Mexico, while Wu *et al*. (2004) evaluated only two conservation easement policies. Second, this study uses a state-of-art physical model to estimate $NO_3$-N concentrations in the Mississippi River, while Wu *et al*. (2004) used simple environmental production functions to estimate $NO_3$-N runoff beyond the root zone. Thus, this study should provide a more accurate assessment of nitrate water pollution.

## The Study Region

The UMRB encompasses approximately 119 million acres in six states: Illinois, Indiana, Iowa, Minnesota, Missouri, and Wisconsin. The three major rivers in the UMRB are the Mississippi, the Minnesota, and the St. Croix. This study covers the area above the mouth of the Missouri River, which accounts for about 109 million acres. The term UMRB refers to this smaller area in this study.

The climate of the UMRB is subhumid continental. The average monthly maximum temperature ranges from –9.8˚C in January in central Minnesota, to 31.7˚C in July in central Missouri. The average annual precipitation ranges from 575 millimeters in the western part of Minnesota, to 981 millimeters in the central part of Illinois. About 75% of the annual precipitation falls during corn growing season from April to October. Soil type in the basin ranges from heavy, poorly drained clay soil to light, well-drained sands.

In most parts of the UMRB, agriculture is the dominant land use. Table 1 indicates that nearly 69% of total land is used for agriculture and pasture. Corn, soybeans, and alfalfa are the major crops in the basin. Corn and soybeans cover 47% of land and account for 68% of cropland and pastureland in the basin. Major cropping systems are corn-soybean rotations and continuous corn, accounting for 62 and 6% of crop and pasture lands, respectively. Conventional tillage is a common practice, accounting for 59% of corn and soybean acreage. In particular, 86% of continuous corn is produced using conventional tillage. Conservation tillage, such as no-till and reduced tillage, accounts for only 41% of corn and soybean acreage in the basin.[1] In 1997, about 3% of cropland was enrolled in the CRP. The annual rental rates range from $15.40 to $112.60, with an average of $78.30 in the basin.

## The Modeling Framework

This section presents the integrated modeling framework to evaluate alternative policies for reducing nitrogen loads from the UMRB to the Gulf of Mexico. The framework, illustrated in figure 1, is built upon the 1982, 1987, 1992, and 1997 NRI - the most comprehensive surveys of soil, water, and related resources ever conducted in the U.S. The NRI, conducted by the Natural Resource Conservation

**Table 1**
Major Land Uses in the Upper Mississippi River Basin

| Land Use | Acreage (1,000 acres) | Share (%) |
|---|---|---|
| Agriculture/Pasture | 68,374 | 65.6 |
| Corn | 28,119 | 27.0 |
| Soybeans | 20,762 | 19.9 |
| Hay | 6,963 | 6.7 |
| Other crop/pasture | 12,530 | 12.0 |
| CRP | 3,085 | 3.0 |
| Forest | 24,537 | 23.5 |
| Urban | 5,611 | 5.4 |
| Water | 2,600 | 2.5 |
| Total | 104,208 | 100.0 |

[a] Double ruled rows indicate a breakdown of agriculture/pasture.

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[1] Conservation tillage refers to any tillage operation that leaves at least 30% of crop residue after harvesting. Any tillage operation leaving less than 30% of crop residue is classified as conventional tillage.

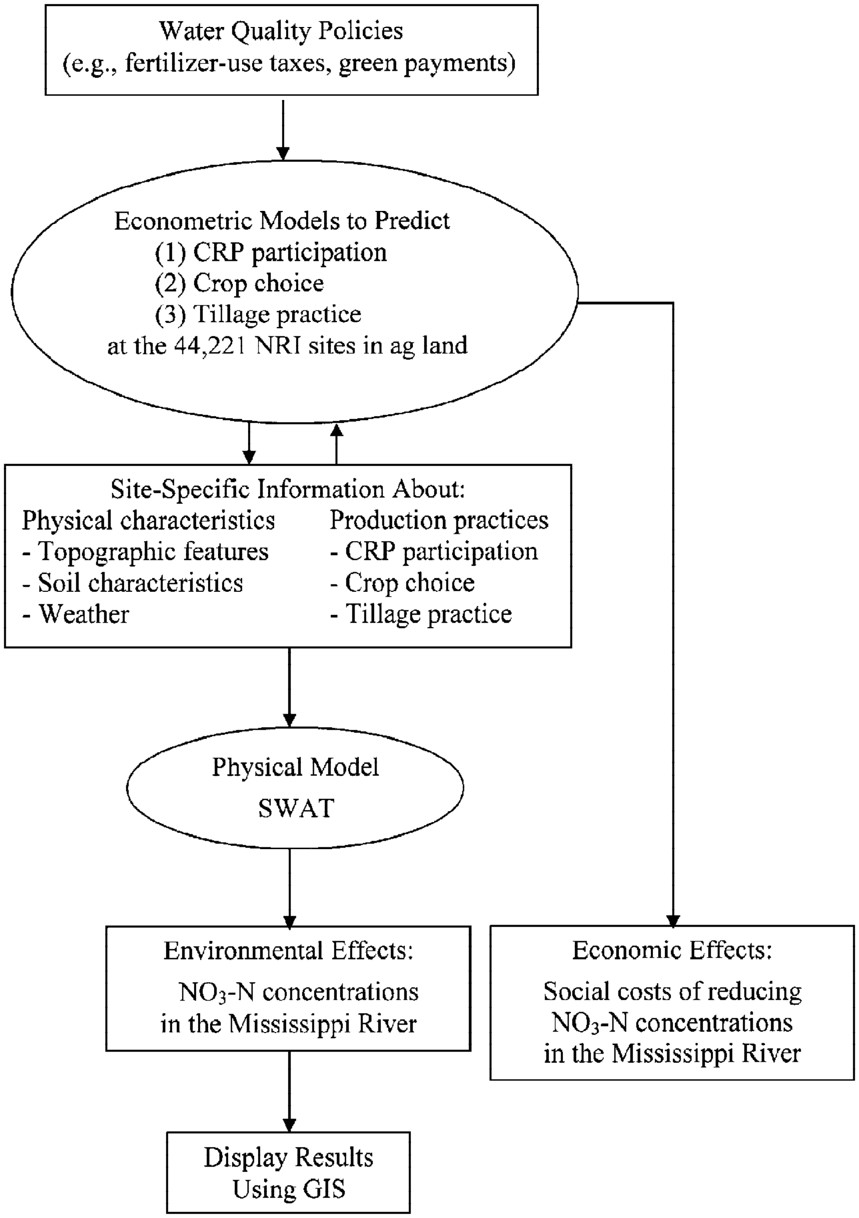

**Figure 1.** The Modeling Framework

Service (NRCS) of the U.S. Department of Agriculture (USDA) every five years, is a scientifically based, longitudinal panel survey that contains information on nearly 800,000 sample sites across the continental U.S. At each site, information on nearly 200 attributes is collected, including cropping history, soil properties, and crop management practices. The NRI also contains an expansion factor to indicate the acreage each site represents. Total acreage in the basin can be estimated by summing the expansion factors for all sites. In the UMRB, there is a total of 112,740 sites, of which 48,284 were located in agricultural and CRP lands in 1997.

Using the 1982, 1987, 1992, and 1997 NRIs and economic data, three econometric models are estimated to predict land use and farming practices under alternative policies in the UMRB. These predicted changes are then fed into the physical model, the SWAT, to predict their impact on $NO_3$-N concentrations at the mouth of the UMRB located at the USGS Gage Station near Grafton, Illinois. The spatial distribution of $NO_3$-N loads is displayed using the GIS interface of the SWAT model. This integrated framework allows region-scale policy simulations while incorporating site-specific information. The major components of the framework are described below.

## *The Econometric Models*

Three econometric models are estimated to predict farmers' decisions regarding: (1) the CRP participation; (2) crop choice; and (3) tillage practice. The CRP model predicts farmers' decisions as to whether or not to participate in the CRP at each NRI site in agricultural land in the UMRB. The crop choice model predicts farmers' choice of crop at each NRI site in agricultural land (*i.e.* corn, soybeans, hay, or other crops). The tillage model predicts farmers' choice of tillage practices (conventional or conservation tillage), conditional on the choice of crop. Each model is specified as the logistic functional form:

$$\text{Prob}_{ij} = \frac{\exp(\beta_i' x_{ij})}{\sum_j \exp(\beta_i' x_{ij})}, \quad i = 1, 2, ..., I; \; j = 1, 2, \ldots, J, \tag{1}$$

where $\text{Prob}_{ij}$ is the probability of choosing crop or practice $i$ at NRI site $j$, and $x_{ij}$ is a vector of independent variables affecting the farmer's choice. The logistic specification can either be derived from a utility or profit maximization framework, as in Wu *et al*. (2004), or be treated simply as a choice of functional form, as in Lichtenberg (1989). The first approach has the advantage of providing a theoretical link between the form of utility or profit functions and the adoption probability. However, it requires specific assumptions about the distribution of the error term in the utility or profit function. The second approach (*i.e.*, treat it as a function form) does not require those assumptions. In addition, the logit model has been shown to outperform other flexible functional forms, such as the Almost Ideal Demand System or translog (Lutton and LeBlanc 1984).

The logit models have been widely used in economic analysis, including the study of the choice of transportation modes, occupations, and asset portfolios. In agriculture, it has been used to model farmers' land allocation decisions (Lichtenberg 1989; Wu and Segerson 1995; Hardie and Parks 1997), the choice of irrigation technologies (Caswell and Zilberman 1985), and the choice of alternative crop management practices (Wu and Babcock 1998).

For the CRP model, the decision is whether or not to participate in the CRP (*i.e.*,

$i = 0, 1$). The important variables affecting farmers' CRP participation decisions include CRP rental rates and opportunity costs of participation. To measure the opportunity cost of participation, we include the following variables as independent variables in the model: (*i*) expected revenue for corn production at the county level (the most detailed data available); (*ii*) variables measuring land quality at individual NRI sites, such as slope, erodibility, water holding capacity, organic matter percentage, soil pH, and soil permeability; (*iii*) variables measuring weather conditions and production risks, such as the mean and variance of maximum temperature and precipitation during corn growing season; (*iv*) input prices; and (*v*) state dummies reflecting differences in farming practices across states.[2]

For the crop choice model, the decision is whether to grow corn, soybeans, hay, or other crops (*i.e.*, $i = 0, 1, 2, 3$). The independent variables for the crop choice model include: (*i*) expected revenue from crop production at the county level, (*ii*) input prices, (*iii*) variables measuring land quality at individual NRI sites, (*iv*) variables measuring weather conditions and production risks at individual NRI sites, and (*v*) state dummies reflecting differences in farming practices across states. This crop choice model is a modification of the crop choice model estimated by Wu *et al*. (2004). The main difference between the two is that we include expected revenues and input prices as separate variables to facilitate the estimation of the effect of the fertilizer-use tax on crop choice, while Wu *et al*. (2004) included expected profits as independent variables in their crop choice model.[3]

For the tillage model, the choice is whether or not to adopt conservation tillage (*i.e.*, $i = 0, 1$). The key independent variable for the tillage model is the difference in production costs between conventional and conservation tillage. Other variables affecting tillage practices include weather and soil conditions, because conservation tillage is more suitable for some soils and weather conditions than for others. The tillage model used in this study was taken from Wu *et al*. (2004).

Using the econometric models, the total acreages of CRP ($A_{CRP}$), individual crops ($A_i$), and conservation tillage ($A_{conserv}$) in a subbasin are estimated using the following equations:

$$A_{CRP} = \sum_j \text{Prob}(CRP)_j \quad xfactor_j\,, \tag{2}$$

$$A_i = \sum_j \text{Prob}(crop\ i)_j \quad xfactor_j\,, \tag{3}$$

$$A_{conserv} = \sum_j \sum_i \text{Prob}(conservation\ tillage|crop\ i)_j \quad \text{Prob}(crop\ i)_j \quad xfactor_j\,, \tag{4}$$

where $xfactor_j$ measures the acres that NRI site $j$ represents;[4] the probability of conservation tillage, conditional on the choice of crop, Prob ($conservation\ tillage|crop\ i)_j$, is

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[2] Several studies (*e.g.*, Cooper and Osborn 1998; Parks and Schorr 1997; Johnson, Misra, and Ervin 1997) have investigated factors affecting CRP enrollments and found that the spatial location of a parcel relative to metropolitan areas and farmer characteristics, such as age and education, are important. However, because the NRI data do not identify the location of individual NRI sites (due to confidentiality issues), we cannot include spatial variables, such as the distance to the closest metropolitan area, as independent variables nor farmer characteristics, such as age and education.

[3] A complete description of the econometric models and the estimated coefficients are available upon request.

[4] According to the NRI users' guides, xfactor specifies the number of acres that a sample point represents when statistical estimates are derived using the NRI database. This weight must be used for all tabulations and analyses—whether estimating average erosion rates, acreages, percentage figures, or margins of error; otherwise, results will be biased.

estimated using the tillage model; and the probability of crop choice, Prob(*crop i*)$_j$, is estimated using the crop choice model.

Based on the predictions of crop choices at each NRI site in 1998 and 1999, the probabilities that alternative cropping systems are adopted at each NRI site are estimated by:

$$\begin{aligned}\text{Prob}(\textit{corn} - \textit{soybean rotation})_j &= \text{Prob}(\textit{corn in } 98|\textit{crop choice in } 97)_j \\ &\quad \text{Prob}(\textit{soyb in } 99|\textit{corn in } 98)_j \\ &\quad + \text{Prob}(\textit{soyb in } 98|\textit{crop choice in } 97)_j \\ &\quad \text{Prob}(\textit{corn in } 99|\textit{Soyb in } 98)_j ,\end{aligned} \tag{5}$$

where the conditional probabilities are estimated using the crop choice model, which includes dummy variables for the previous year's crop as independent variables and thus can make crop choice prediction conditional on the crop choice at the site in the previous season. Based on equation (5), the acreage of land under corn-soybean rotation in 1998 and 1999 is then estimated by:

$$A_{\textit{corn-bean rotation}} = \sum_j \textit{Prob}(\text{corn - soyb rotation})_j \quad \textit{xfactor}_j . \tag{6}$$

Acreages of continuous corn and continuous soybean are similarly estimated.

### *Data and Estimation of the Econometric Models*

The estimation of the three sets of econometric models requires a substantial amount of data, which must be integrated from multiple sources. These data include: (*i*) the choice of crop, tillage, and CRP participation at each NRI site; (*ii*) expected output and input prices; (*iii*) expected yields; (*iv*) measures of production risks; and (*v*) land characteristics at each NRI site (soil properties, topographic features, climate conditions). Information on site characteristics is needed because we only have the county-level data on crop yields. Site characteristics are used to capture the differences in land quality among NRI sites within a county. Below we provide a description of these data.

Data on crop choice, tillage practice, and CRP participation at each NRI site are derived from the NRIs. Each NRI survey contains crop choice information for four years (the current year plus the previous three years) and tillage information for one year. Information on CRP participation was only collected from the 1992 and 1997 NRIs. Thus, we have crop choice information for 16 years at each NRI site, tillage information for three years,[5] and CRP participation information for two years. Pooling the time-series and cross-sectional data results in 506,652 observations for the crop choice model (42,221 agricultural NRI sites x 12 years),[6] 126,663 observations for the tillage model (42,221 x 3), and 84,442 observations for the CRP model (42,221 x 2). For computational feasibility, we randomly selected 10% of the observations for estimation of the econometric models.

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[5] The 1997 NRI data used here contained crop information, but not tillage information.

[6] To capture the restrictions imposed by crop rotations, dummy variables are included to reflect the crop choice in the previous year at each NRI site in the crop choice model. Thus, the pooled time-series and cross-sectional data for the crop choice model have observations for 12 years instead of 16 years.

The expected revenue for a crop in period $t$, $E(R_t)$, is estimated by:

$$E(R_t) = E(p_t)E(y_t) + \rho(p, y)\mathrm{sd}(p_t)\mathrm{sd}(y_t), \tag{7}$$

where $E(p_t)$ is the expected price; $E(y_t)$ is the expected yield; $\mathrm{sd}(p_t)$ and $\mathrm{sd}(y_t)$ are the standard deviation of price and yield, respectively; and $\rho$ is the correlation coefficient between the price and yield. Expected prices for corn are specified as the average futures prices in its planting season, which are estimated as the average of the first and second Thursday closing prices in March at the Chicago Board of Trade (CBT) for December corn. Expected prices for soybeans are estimated as the average of the first and second Thursday closing prices in March on the CBT for November soybean. The expected value and the standard deviation of corn and soybean yields are estimated for each county using the National Agricultural Statistics Service (NASS) county crop data for the period of 1975–98. Following Chavas and Holt (1990), a trend model of $y = \alpha + \beta t + \varepsilon$ is estimated for corn and soybean yields using ordinary least squares. The predicted values are taken as expected yields. The residuals are used to derive the standard deviation. The standard deviation of corn and soybean prices is estimated based on adaptive expectations following Chavas and Holt (1990):

$$\mathrm{sd}(p_t) = \left\{ \sum_{j=1}^{3} \omega_j \left[ p_{t-j} - E_{t-j-1}(p_{t-j}) \right]^2 \right\}^{0.5}, \tag{8}$$

where $p_{t-j}$ is the annual average market price for corn in period $t - j$, and $E_{t-j-1}$ is the expectation, at planting time in year $t - j$, of the price for the crop at harvesting in year $t - j$. The weights $\omega_j$, 0.5, 0.33, and 0.17 are taken from Chaves and Holt (1990).

The county-level data on CRP annual rental rates are obtained from the Farm Service Agency. Wage rates and the fertilizer price index are obtained from the NASS. All input and output prices, and the CRP rental rates, are normalized by the index of prices paid by farmers published by the USDA.

The NRI also contains information about land characteristics at each NRI site, including land capacity class, slope, and wind and water erosion rates. Other site-specific characteristics, such as water holding capacity, organic matter percentage, soil pH, and soil permeability, are obtained by linking NRI to the SOIL5 database developed by the NRCS. Weather data are obtained from the Midwestern Regional Climate Center. Using historical weather information from the nearest weather station, the mean and standard deviation of maximum daily temperatures and precipitation during corn growing season are estimated for each NRI site.

## *The Physical Model*

The Soil and Water Assessment Tool (SWAT) is used to assess the level of $NO_3$-N concentrations in the Mississippi River under different policies. SWAT is a watershed (or river basin) scale water balance simulation model developed by the Agricultural Research Service of the USDA. SWAT can predict the impact of crop management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over a long period of time (Neitsch *et al*. 2002). SWAT requires extensive information on topography, soil properties, weather, and land management practices in the watershed.

The spatial units of SWAT simulations are watershed and subbasins. The watershed is the overall hydrological unit, representing the entire area to be simulated. The watershed is partitioned into a number of subbasins. Each subbasin possesses a geographic position in the watershed and is spatially related to adjacent subbasins. Each subbasin is further divided into hydrologic response units (HRUs), which are virtual units of SWAT simulations. The geographical locations of HRUs within a subbasin are not specified. Each HRU represents a unique combination of land use and soil type. For example, if a subbasin has two land uses and two types of soil, SWAT will construct four HRUs for the subbasin, each representing a unique combination of land use and soil class. The inclusion of HRUs enables SWAT to account for the complexity of the landscape within the subbasins. Thus, SWAT can take two levels of the spatial heterogeneity into account. The first level (subbasin) supports the spatial heterogeneity associated with hydrology, and the second level (HRU) incorporates the spatial heterogeneity associated with land use and soil type. Since the spatial heterogeneity significantly affects the levels of runoff, leaching, and associated agricultural pollutants, SWAT is one of the best available tools for analyzing the issues related to agricultural land use changes and water pollution under spatially heterogeneous conditions.

### *Data and Model Development of SWAT*

SWAT requires extensive data on topography, soil, weather, land use, and management practices. These data are collected and applied in three steps in the model development. The steps are: (*i*) watershed delineation; (*ii*) land use and soil classification; and (*iii*) land management schedule specification. This study uses ArcView interface of SWAT 2000 (AVSWAT) to automate most of the model development steps.

The watershed delineation carries out an advanced GIS functions to aid the user in segmenting watersheds into hydrologically connected subbasins. The primary data required for this process are topography in the watershed, which is used to calculate slope and slope length in each cell, to determine hydrologic channel, and to delineate subbasins. We use the 1-degree Digital Elevation Model (DEM) data from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) version 3 CD developed by the U.S. Environmental Protection Agency for watershed delineation, which results in a total of 118 subbasins, following the 8-digit hydrological unit boundaries.

In the second step, unique combinations of land use and soil type for each subbasin are identified based on the spatial distribution of land use and soil types. Soil classification is performed using the State Soil Geographic (STATSGO) digital soil association map developed by the NRCS. Land classification is performed based on the Land Use and Land Cover (LULC) spatial map developed by the U.S. Geological Survey (USGS 2005). The LULC data provides spatial information on broad land use classes, such as urban, agriculture, forest, and water. Detailed information about crop choices and farming practices is integrated into the LULC data by the following procedure. First, we estimate the land allocation among broad uses (agriculture, forest, urban, and water) for each subbasin. We then divide agricultural land use into seven subcategories (corn-soybean rotation with conventional tillage, corn-soybean rotation with conservation tillage, continuous corn with conventional tillage, continuous corn with conservation tillage, alfalfa hay, CRP, and other cropland and pastureland). For example, suppose that 45% of one subbasin is identified as agricultural land, and the economic models predict that 10% of agricultural land is allocated to corn-soybean rotation with conservation tillage. Then, by integrating these estimates, AVSWAT determines that corn-soybean rotation with conservation tillage accounts for 4.5% (45*0.1) of total land area in the subbasin. This procedure is applied to each of 118 subbasins in the UMRB. As a result, we obtained a total of 10 land use categories (seven agricultural land use classes and three non-agricultural land uses),[7] and a total of 1,410 HRUs in the UMRB.

The land management schedules describe management practices for each type of land use in the subbasins (*e.g.*, timing and amount of fertilizer applications). The schedules for crop management practices are determined based on Neppel (2001); McIsaac, Mitchell, and Hirschi (1995); Kellie, Eilers, and Santelmann (2002); and suggestions from local agricultural experiment stations. For "other crops" and non-agricultural land use (*i.e.*, forest and urban), the default schedules generated by SWAT are used. Although many types of tillage practices are referred to as conservation tillage, we use no-till[8] as a representative of conservation tillage practice in the basin.

Finally, SWAT requires weather information, including precipitation, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity. If daily precipitation and air temperatures are available, they can be input directly into the model. If not, daily values for these variables can be generated by the SWAT built-in weather generator. Solar radiation, wind speed, and relative humidity are always generated. In this study, all weather information required for SWAT simulations is generated based on monthly weather statistics from about 60 weather stations in the UMRB. The ArcView interface automatically selects the nearest weather station for each subbasin and generates weather variables based on the historical statistics.

## Methods For Policy Evaluation

Using the integrated modeling framework, we evaluate the relative efficiency of four commonly suggested policies for reducing nitrogen runoff from the UMRB: (*i*) taxes on chemical fertilizer use; (*ii*) incentive payments for cropland retirement; (*iii*) incentive payments for conservation tillage; and (*iv*) incentive payments for corn-soybean rotations. The relative efficiency of these policies is evaluated based on the social costs for achieving different levels of reduction in $NO_3$-N concentrations at the USGS Gage Station (#05587455) near Grafton, Illinois, under these policies. The impacts of these policies on crop choices, CRP participation, rotation, and tillage practices are also estimated.

To evaluate policy impacts, we must first establish a baseline. To this end, we first calculate the probabilities of farmers' choice of alternative crops and management practices at each NRI site in 1998 and 1999 by substituting the values of independent variables for these two years into the econometric models. We then estimate the acreages of CRP, individual crops, and conservation tillage for each subbasin using equations (2-6). Finally, we run SWAT to predict $NO_3$-N concentrations at the USGS Gage Station (#05587455) near Grafton, Illinois, based on the estimated land use and farming practices in each subbasin. We use the predicted land use and $NO_3$-N concentrations as a baseline for policy evaluations.[9]

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[7] Some subbasins do not contain the hydrologic response unit for water because their areas are too small to be modeled.

[8] No-till is a method of farming where the soil is left undisturbed from the harvest of one crop to the beginning of next growing season. Soil disturbance occurs only when fertilizer is applied before growing season, and when crop is harvested.

[9] Because all policies, except the CRP, are not expected to affect crop yields significantly, they are not expected to significantly affect crop prices. Considering the price-feedback effects in the evaluation of CRP would improve the quality of the analysis. However, data are not readily available to measure such price feedback effects.

Once the baseline is established, we then evaluate the policy impact on land use and nitrate water pollution. Several independent variables in the econometric models are “policy variables” because they are directly affected by policies. For example, policymakers can increase CRP participation by raising CRP rental payments. The effect of this policy is simulated by increasing CRP rental rates in the CRP model, holding other variables constant. Similarly, in the incentive payment programs for crop rotations, farmers who grow soybeans after corn or corn after soybeans receive a payment. The effects of the payments are simulated by increasing the expected revenue for the eligible crops in the crop choice model (soybeans after corn or corn after soybeans) by the amount of the payments. In the incentive payment program for conservation tillage, farmers adopting conservation tillage receive a payment. The effect of this payment is simulated by increasing the difference between the production costs for conventional tillage and conservation tillage in the tillage model by the amount of conservation payments.

By setting the policy variables to a range of values, supply curves are generated for CRP acreage, crop rotation, and conservation tillage. These supply curves show the acreage of adoption under different levels of payments (see the upward-sloping curve in figure 2 for an illustration). Changes in land use are then translated into changes in $NO_3$-N concentrations in the Mississippi River through SWAT simulations. Results are generated for different levels of reduction in $NO_3$-N concentrations (see the downward-sloping curve in figure 2).

Social costs for achieving different levels of reduction in $NO_3$-N concentrations under each policy can be estimated based on the estimated the relationships between payment levels, adoption rates, and percentage reductions in $NO_3$-N concentrations. Specifically, for each targeted level of reduction in $NO_3$-N concentrations, the required adoption level can be determined based on the relationship between adoption rates and percentage reductions in $NO_3$-N concentrations (*i.e.*, the downward-sloping curve in figure 2). The corresponding payment level is then determined based on the supply curve of conservation practice (*i.e.*, the upward-sloping curve in figure 2). For example, as shown in figure 2, a $C$% reduction in $NO_3$-N concentration requires $A_C$ acres of land adopting the conservation practice. The corresponding payment rate is $P_C$. The area under the supply curve between $A_0$ and $A_C$ (*i.e.*, the shaded area) is the social cost for achieving the targeted level of reduction in $NO_3$-N concentrations. The rectangle area $OP_CBA_C$ is the total government payment. The difference between the total government payment and total social cost is the producer surplus.

Social costs for achieving different level of reduction in $NO_3$-N concentrations under the fertilizer use tax are estimated using the following procedure. First, we estimate crop choice at each NRI site for different tax rates $\tau$ by changing the fertilizer price in the crop choice model. Second, we estimate the fertilizer application rate for corn by using $N(\tau) = N_0(1 + \tau)^{-\varepsilon}$, where $N_0$ is the nitrogen application rate without any tax, $\tau$ is the tax rate, and $\varepsilon$ is the own price elasticity of nitrogen application rate. We set $N_0 = 202$ kg ha$^{-1}$ based on suggestions from a staff member of the Soil and Water Conservation Society and data from Iowa Agricultural Experimental Station, and $\varepsilon = -0.21$ based on a study of demand for nitrogen fertilizer in corn production in the U.S. Midwest by Denabaly and Vroomen (1993). Third, based on the estimated crop choice and nitrogen application rates, we run SWAT to estimate the $NO_3$-N concentrations at the mouth of the UMRB under different levels of taxes. Fourth, we calculate aggregate farm profit under different tax rates using:

$$\sum_{i=1}^{I} \left[ A_i(\tau) \left\{ p_i Y_i[N_i(\tau)] - C_i - (1 + \tau) w N_i(\tau) \right\} \right], \tag{9}$$

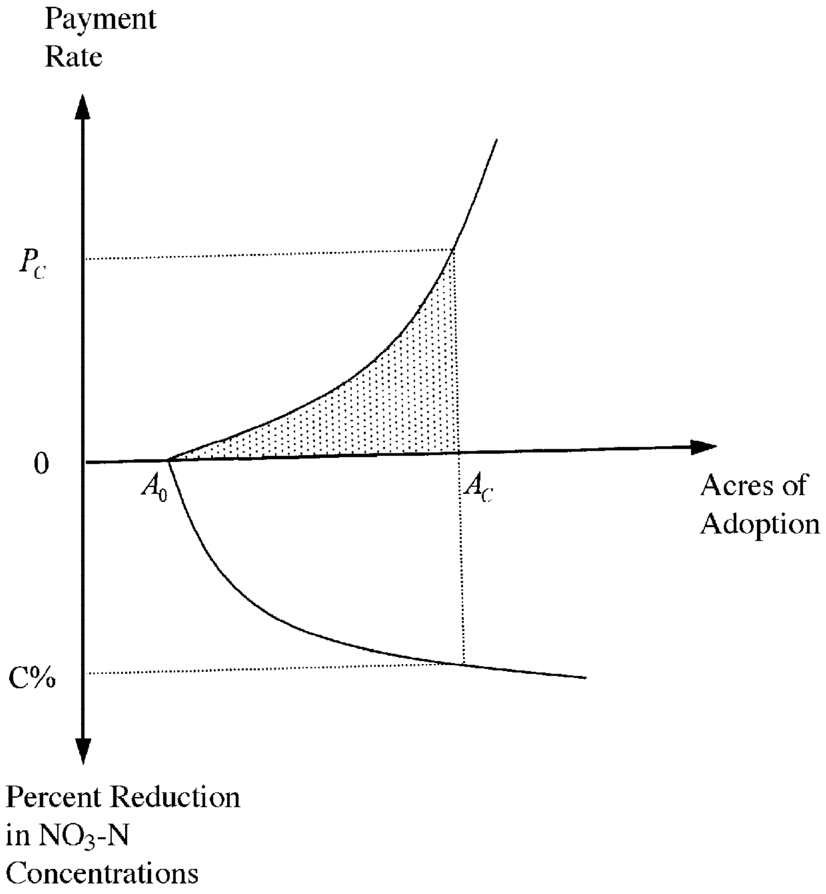

**Figure 2.** Measuring Social Costs of Reducing $No_3$-N Concentrations

where $A_i(\tau)$ is the total acreage of crop *i* under the tax, $p_i$ is the price of crop *i*, $Y_i[N_i(\tau)]$ is the yield of crop *i* under the fertilizer tax, $C_i$ is the production cost of crop *i* excluding the cost of nitrogen fertilizer, and *w* is the fertilizer price. Corn yields under different levels of nitrogen application rates, $Y_i[N_i(\tau)]$, are calculated using the yield response functions from Stecker *et al.* (1995). These quadratic yield response functions relate corn yields to nitrogen application rates under continuous corn and corn-soybean rotation. Yields of other crops are assumed not to be affected by the tax. Production costs, $C_i$, are estimated based on Duffy (2000). All prices and yields (except corn yields) are obtained from the NASS (1979–2001). Finally, social costs for achieving a given level of reduction in $NO_3$-N concentrations are estimated by subtracting the tax revenue from farmers' total profit loss under the corresponding level of tax.

## Results

### *The Policy Impacts on Land Use and Farming Practices*

The policy impacts on land use and farming practices in the UMRB are estimated using equations (2-6). Figure 3 presents the estimated effect of the fertilizer-use tax on cropland allocation. As the tax rate increases, the acreage of corn and soybeans decreases, while the acreage of hay and other crops increases.[10] In addition, corn acreage is more responsive to the tax than soybean acreage. These results are as expected because corn and soybeans require more fertilizer application than hay and other small crops, and an increase in fertilizer prices will increase the relative profit-

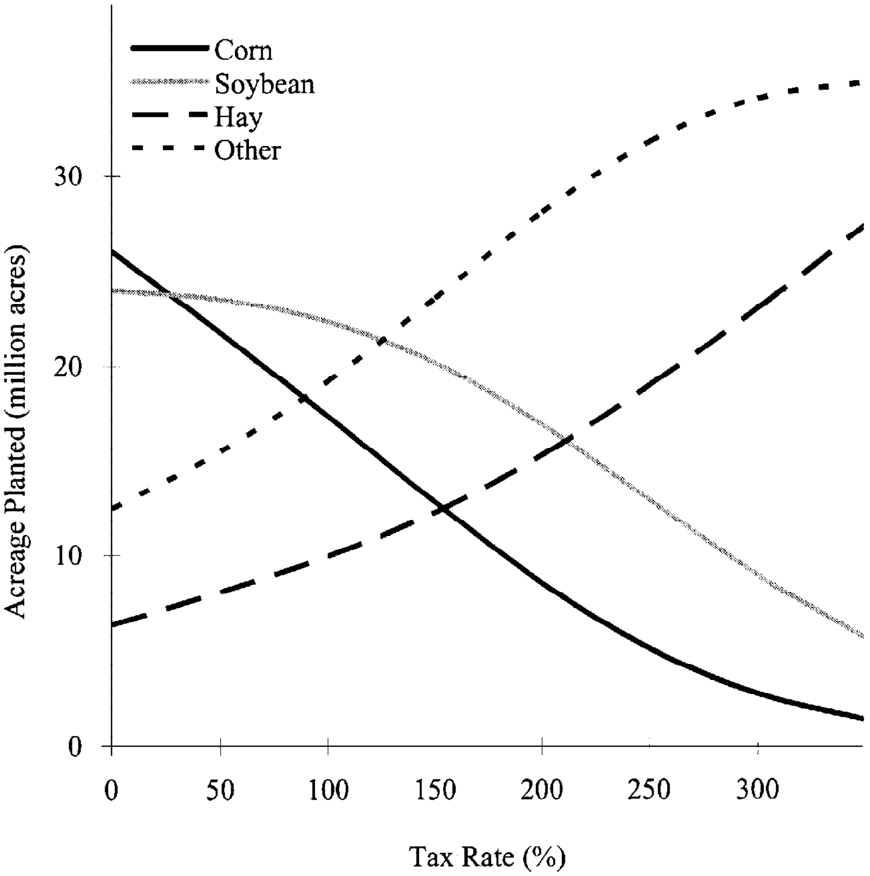

**Figure 3.** Estimated Acreage Responses to the Fertilizer-Use Tax in the Upper Mississippi River Basin

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[10] Figure 3 shows the predicted acreages of the four crops at the baseline when the tax rate is zero. The predicted acreages of hay and other crops closely matched the reported acreages of these crops. The model overpredicts the acreage of corn and underpredicts the acreage of soybeans, although the predicted acreage of corn and soybeans closely matched the reported total acreage of the two crops.

ability of hay and other crops. However, as predicted by previous studies (*e.g.*, Huang and Lantin 1993 and Whittaker *et al*. 2004), the acreage responses are inelastic.

Figure 4 shows the estimated effect of CRP rental rates on CRP acreage in the UMRB. As the rental rate increases, the acres of cropland enrolled in the CRP also increase, but the rate of increase is not constant. Acreage responses are inelastic when the rental rate is below $100 or between $200 and $250, but elastic when the rental rate is between $100 and $200 or above $250 per acre. Most of land enrolled in the CRP from $100–$200 was used to produce hay and other crops. Very few acres of corn and soybeans are enrolled in the CRP when the payment rate is below $250 per acre. This suggests that required payments for CRP participation are higher than the profit forgone, which equals about $200 per acre for corn and $150 per acre for soybeans (Food and Agricultural Policy Research Institute 1996). Higher rental rates may be necessary for at least three reasons. First, although the CRP provides cost-share assistance to participating farmers who establish conservation covers on their CRP land, this assistance covers less than 50% of the participants' costs. The Farm Service Agency (2003) reports that CRP participants receive $145 dollars per acre, on average, for cost-share assistance and incentive payments. Second, when CRP contracts expire, some farmers may want to bring their CRP land back into crop production. The conversion cost could be significant, especially when trees are planted as a land cover. Finally, lands with potential for development during the CRP contract period are not likely to enroll, even if the CRP rental rates cover the agricultural profit forgone.

The effect of incentive payments on conservation tillage adoption is also estimated. Without any payment, 40% of corn and soybean acres adopt conservation tillage. A payment rate of $50 and $100 per acre increases the share of conservation tillage to 61 and 78%, respectively. The large variation in the required payment level

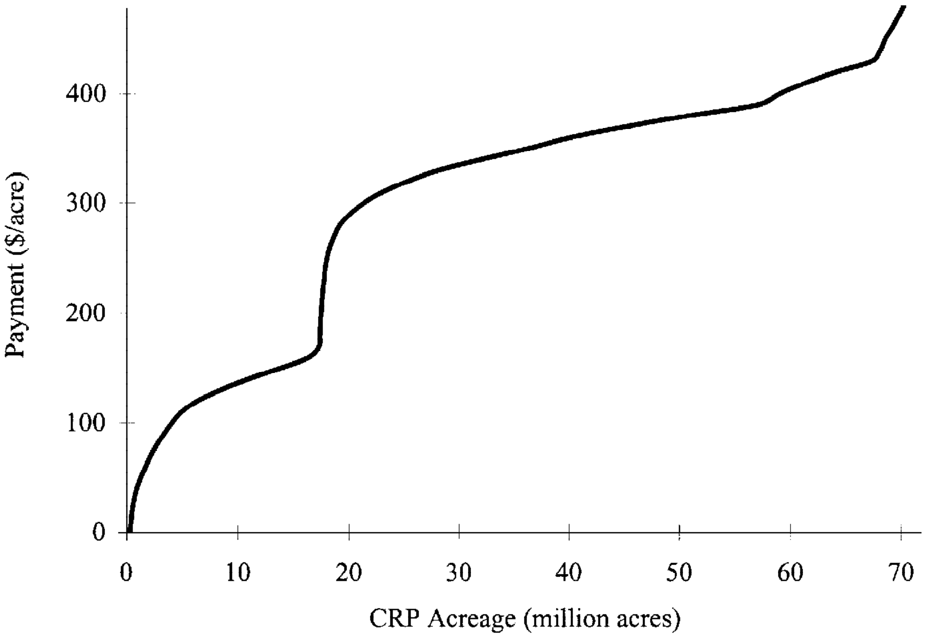

**Figure 4.** Estimated Supply Function of CRP Land in the Upper Mississippi River Basin

for conservation tillage adoption may reflect that conservation tillage may be more suitable for some soils than for others. In general, conservation tillage is not suited for: (*i*) poorly drained soils; (*ii*) less fertile soils; and (*iii*) steep and rough areas. Under those conditions, crop yields and profits under conservation tillage may be substantially lower than those under conventional tillage. In addition, conservation tillage requires special equipment, such as no-till planters and shielded sprayers. It also requires timely weed control, which some farmers may not be able to do.

In a study of conservation tillage adoption in Iowa, Kurkalova, Kling, and Zhao (2003) find that a 30% increase in conservation tillage can be achieved with a payment of $11 per acre. Our estimates of the required payments for the UMRB are higher; a payment of $33 per acre is required for a 30% increase in conservation tillage in the UMRB. The difference may be due to two reasons. First, in Kurkalova, Kling, and Zhao (2003), payments are offered for all crops adopting conservation tillage, while payments in this study are only offered for corn and soybean. Second, the adoption rate of conservation tillage has been historically higher in Iowa than any other states in the UMRB. The 1992 NRI indicates that conservation tillage was used on 40% of cropland in Iowa, but on only 21% of cropland in five other states (Illinois, Indiana, Minnesota, Missouri, and Wisconsin).

Incentive payments for corn-soybean rotations reward farmers who plant corn after soybeans, or soybeans after corn. Currently, 86% of corn and soybean acreage is under corn-soybean rotation. A payment of $50 and $100 per acre increases the share to 88% and 90%, respectively. Given that 86% of corn and soybean acreage is already under corn-soybean rotation, this policy is not likely to have a large impact on $NO_3$-N pollution, a topic which will be focused on next.

### *SWAT Model Validations and Results*

Using the land use data at the baseline, a 20-year run of the SWAT model is conducted. The monthly averages of the simulated stream flow are compared with those reported at the USGS Gage Station (#05587455) on the Mississippi River near Grafton, Illinois, from 1980 to 1999. The difference between the measured and simulated monthly average of stream flow is less than 5%. The simulated $NO_3$-N concentrations are also compared with those observed at the USGS Gage Station. From 1998 to 2000 the observed monthly average of $NO_3$-N concentrations at the USGS Gage Station was 3.14 mg/L. These observed $NO_3$-N concentrations not only include runoffs from crop production, but also from other sources, such as livestock operations, urban runoff, and industrial point source discharges. Goolsby and Battaglin (1997) report that commercial nitrogen fertilizer and legume nitrogen fixing in the UMRB contribute 65% of total nitrogen loads to the Gulf of Mexico. Applying the percentage to the observed $NO_3$-N concentrations of 3.14 mg/L gives 2.04 mg/L, which is close to the monthly average of $NO_3$-N concentrations of 1.99 mg/L estimated by SWAT.

Figure 5 shows the simulated $NO_3$-N concentrations at the end of reaches in each subbasin in the UMRB. The level of concentrations range from 0.18 to 2.1 mg/L, with a basin average of 0.7 mg/L. High $NO_3$-N concentrations tend to occur along the mainstream of the Mississippi River and its major tributaries. In the upper area of the basin, particularly high concentrations are predicted in subbasins 111 and 23. These subbasins have a higher concentration of corn and soybean acreage and more precipitation than the basin average. Lower concentrations occur at many subbasins below these subbasins, due mainly to less intensive row crop production. In the UMRB, the highest concentrations occur in subbasin 90, the confluence of the Mississippi and the Des Moines Rivers. The subbasins along the Des Moines River have areas which produce high concentrations of corn and soybeans and have been identi-

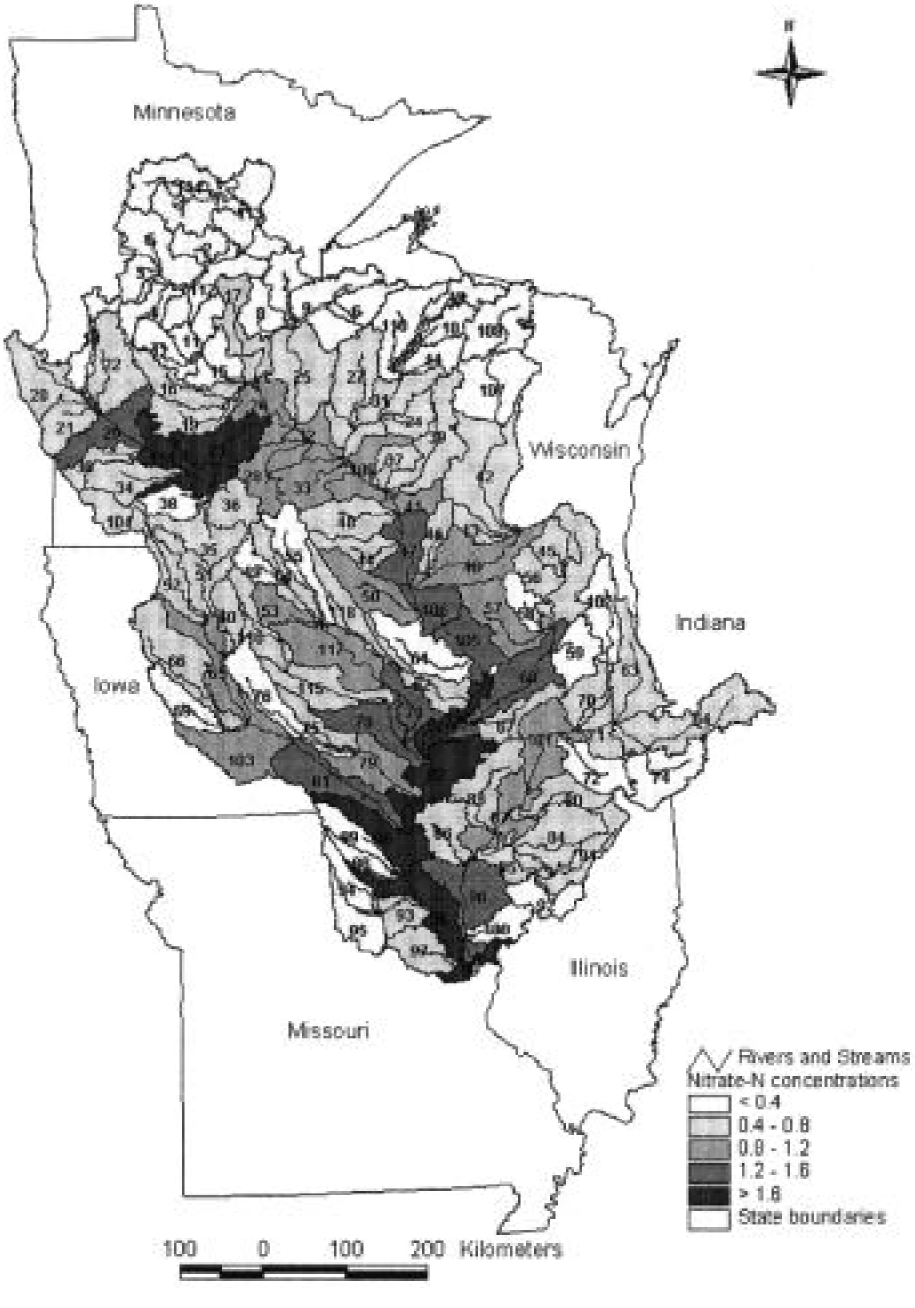

**Figure 5.** Estimated $NO_3$-N Concentrations at the End of Reach in Each Subbasin in the Upper Mississippi River Basin

fied as high-risk areas of $NO_3$-N water pollution in the UMRB. Previous water quality surveys show that $NO_3$-N concentrations in the public water supply in Des Moines, Iowa, often exceed the maximum contamination level of 10 mg/L set by the EPA (United States Geological Survey 2003).

### *The Relative Efficiency of the Four Policies*

Table 2 shows the levels of estimated social cost and $NO_3$-N concentrations at the mouth of the UMRB for different levels of payment and tax rates under the three conservation easement policies and the fertilizer-use tax. The first column shows the level of payment per acre for the adoption of conservation tillage, corn-soybean rotation, or land retirement. The next six columns show the corresponding levels of social cost and $NO_3$-N concentrations under the three conservation easement policies. The last three columns show the tax rate, the levels of social cost, and $NO_3$-N concentrations under the fertilizer-use tax. Payments for conservation tillage can reduce $NO_3$-N concentrations by only about 37% (from 1.99 mg/liter to 1.25 mg/liter), at which all corn and soybean acres are converted to conservation tillage. The potential for the incentive payments for corn-soybean rotations is even more limited. These payments can reduce $NO_3$-N concentrations by only 6% (from 1.99 mg/liter to 1.87 mg/liter). In contrast, the CRP and the fertilizer-use tax can be used to achieve higher levels of reduction in $NO_3$-N concentrations.

To compare the relative efficiency of these four policies, the estimated social costs for achieving different levels of reduction in $NO_3$-N concentrations at the USGS Gage Station near Grafton, Illinois, are shown in figure 6. The fertilizer-use tax is much more cost effective for reducing $NO_3$-N concentrations than the three

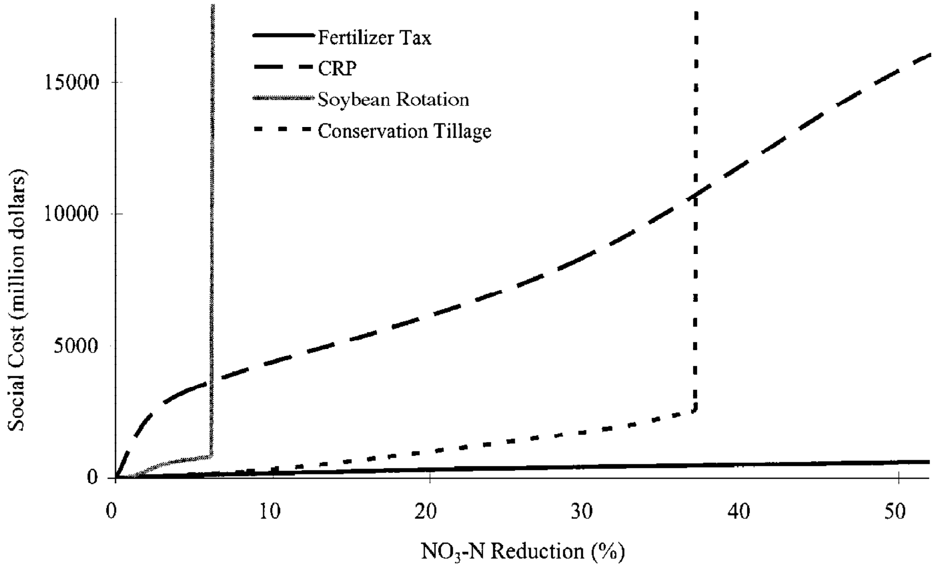

**Figure 6.** The Relative Efficiency of Policies in the Upper Mississippi River Basin for Reducing $NO_3$-N Concentrations at the Mouth of the Basin (Measured at the USGS Gage Station near Grafton, Illinois)

**Table 2**
The Estimated Social Costs and NO3-N Concentrations under Three Conservation Easement Policies and a Fertilizer-Use Tax

| | Conservation Tillage | | Corn-Soybean Rotation | | CRP | | Fertilizer-Use Tax | | |
|---|---|---|---|---|---|---|---|---|---|
| Payment Level ($/acre) | Social Cost (Million Dollars) | $NO_3$-N Concentration (mg/liter) | Social Cost (Million Dollars) | $NO_3$-N Concentration (mg/liter) | Social Cost (Million Dollars) | $NO_3$-N Concentration (mg/liter) | Tax Rate % | Social Cost (Million Dollars) | $NO_3$-N Concentration (mg/liter) |
| 0 | 0 | 1.99 | 0 | 1.99 | 0 | 1.99 | 0 | 0 | 1.99 |
| 50 | 236 | 1.82 | 26 | 1.97 | 30 | 1.98 | 50 | 40 | 1.96 |
| 100 | 792 | 1.64 | 122 | 1.96 | 249 | 1.98 | 100 | 175 | 1.80 |
| 200 | 1,856 | 1.37 | 515 | 1.93 | 2,105 | 1.93 | 150 | 386 | 1.45 |
| 300 | 2,352 | 1.28 | 710 | 1.89 | 3,163 | 1.91 | 200 | 643 | 0.89 |
| 400 | 2,519 | 1.26 | 780 | 1.87 | 16,581 | 0.92 | 250 | 897 | 0.63 |
| 500 | 2,568 | 1.25 | 797 | 1.87 | 21,921 | 0.32 | 300 | 1,109 | 0.58 |

Note: $NO_3$-N concentrations are measured at the USGS Gage Station near Grafton, Illinois (the mouth of the Upper Mississippi River Basin).

easement policies. The fertilizer-use tax not only reduces nitrogen application rates (the intensive margin effect) but also reduces the total acreage of polluting crops (corn and soybeans) (the extensive margin effect). Thus, the tax is very effective in reducing $NO_3$-N concentrations. Furthermore, because of low prices, farmers often apply more fertilizer than needed in case of unexpected weather events. As a result, reduction in nitrogen application rates under the tax does not significantly reduce crop yields and farm profit.

Among the three conservation easement policies, incentive payments for conservation tillage are the most cost effective for reducing $NO_3$-N concentrations. However, this policy can reduce $NO_3$-N concentrations by no more than 37%. The potential for the incentive payments for corn-soybean rotations is even more limited. These payments can reduce $NO_3$-N concentrations by only 6%. Further reduction is not possible because at this level all continuous corn has already been converted to corn-soybean rotation. Such a small effect is not unexpected, since 86% of corn and soybean acres are already in corn-soybean rotations.

Among the four policies, the CRP is least cost-effective for reducing $NO_3$-N concentrations in the Mississippi River. Although the CRP can be used to achieve a large reduction in $NO_3$-N concentrations, it has to enroll non-polluting crops first. When the rental rate is below $200 per acre, very few acres of polluting crops (corn and soybean) will be enrolled in the CRP.

## Conclusions

This study integrates economic and physical models to estimate the social costs for reducing $NO_3$-N loads from the UMRB to the Gulf of Mexico under four policies. The economic models predict three land-use decisions (CRP participation, crop choice and rotation, and conservation tillage adoption) at more than 44,000 NRI sites in the UMRB under the policies. The physical model then estimates the effect of land use decisions on $NO_3$-N concentrations at the mouth of the UMRB.

Results suggest that the fertilizer-use tax is much more cost effective than the three conservation easement policies. However, it is more difficult politically to institute the fertilizer-use tax than to implement the conservation easement policies. Among the three conservation easement policies, payments for conservation tillage are most cost effective, but can reduce $NO_3$-N concentrations by only 37%. The potential for incentive payments for corn-soybean rotations is even more limited. These payments also impose a higher cost to society than the payments for conservation tillage. The CRP can be used to achieve the largest reduction in $NO_3$-N concentrations, but is the least cost effective among the four policies considered in this study.

Several caveats are in order before we conclude. First, these four policies are evaluated based on their efficiency for controlling nitrate water pollution. Their relative efficiency for controlling other types of pollution may be different. For example, the CRP has been found to be quite effective for controlling soil erosion, although it is not efficient for controlling nitrate water pollution. Second, this study does not address political economy issues associated with the policies. Although the fertilizer-use tax is more cost-effective than the three conservation easement policies, it is less feasible politically than the conservation easement policies. Finally, $NO_3$-N concentrations estimated in this study should be considered as an approximation for potential nitrate water pollution, even though SWAT is a state-of-art simulation model that incorporates field-level information about farmers' production practices and physical characteristics. Continuous improvements in data and modeling techniques will enhance our ability to provide more reliable estimates of nitrate water pollution.

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