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Tradable Permits for Controlling Nitrates in Groundwater at the Farm Level: A Conceptual Model

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ABSTRACT

Nitrate contamination of municipal and domestic well water supplies is becoming an increasing problem in many rural and urban areas, raising the cost of providing safe drinking water. The objective of this paper is to describe a marketable permit scheme that can effectively manage nitrate pollution of groundwater supplies for communities in rural areas without hindering agricultural production in watersheds. The key to implementing this scheme is being able to link nitrate leaching from nitrogen fertilizer applied to crops at a farm to nitrate levels measured at a drinking water well.

Key Words: *agriculture, groundwater pollution, leaching, nitrates, pollution trading.*

Nitrate contamination of municipal and domestic well water supplies is becoming an increasing problem in many rural and urban areas, raising the cost of providing safe drinking water. A well-water survey conducted by the U.S. Environmental Protection Agency (EPA) found nitrates in over half of community water wells and almost 60 percent of rural domestic wells in the U.S. (Environmental Protection Agency). Nitrate contamination of water may pose a threat to human health[1], which would likely result in additional cleanup costs to protect health. Treating the drinking water contamination problem can add several hundred dollars per year to the household cost of maintaining private wells and from $2 to almost $50 per year to the household water bill in larger municipal systems (O'Neil and Raucher).

Sources of nitrates in the groundwater include commercial fertilizers for crops, manure, septic systems, lawn fertilizers, feedlots, and municipal and industrial waste (Wall). Though agricultural production practices are clearly only one of many sources of nitrates to groundwater, they can be a significant source in farming areas where nitrogen fertilizer is heavily applied to crops. Excess nitrogen not used by the crops has the potential to leach below the root zone into groundwater. Because agriculture is believed to be a substantial contributor to nitrate pollution in groundwater, and because the consistency of agriculture planting methods lends itself to quantitative analysis, this paper focuses on the implementation of a tradable permit scheme at the farm level.

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[1] These include methemoglobinemia (blue-baby disease) in infants and gastric cancer in adults (Wall).

hindering agricultural production in watersheds. The key to implementing this scheme is being able to link nitrate leaching from nitrogen fertilizer applied to crops at a farm to nitrate levels measured at a drinking water well. The proposed approach is feasible because soil models can predict nitrate leaching losses from the crop root zone and contaminant transport models can simulate movement of nitrates in groundwater systems. When soil and groundwater processes are linked, each farm's contribution to nitrate contamination levels at groundwater wells can be estimated. This means that each farm can be held accountable for its specific portion of contamination, thus converting nitrate contamination of groundwater from a nonpoint-source problem to a point source problem.

Traditionally, nitrate groundwater pollution has been analyzed as a nonpoint-source problem, a realistic approach given the lack of data relating nitrogen application to leaching. However, this informational gap is diminishing as site-specific data is becoming accessible, both as raw data from field experiments and as output from models developed to simulate nitrate transport through the crop root zone. Several studies have integrated sample or simulated nitrate leaching data into an economic framework to evaluate the effect of regulatory options designed to reduce groundwater pollution (Fleming; Mapp *et al.*).

A few studies have included the biophysical processes of leaching to examine the effectiveness of leachate permits (Pan and Hodge; Thomas). However, the permits in these studies are traded based on the quantity of nitrates estimated to enter the groundwater, not nitrate levels at groundwater wells. It is more relevant to assess nitrate levels at a well (rather than nitrate loadings into the groundwater) using a water quality test performed on a sample of groundwater taken from the well. Health impacts from nitrates are directly related to individuals in the community ingesting contaminated drinking water.

Nitrate leaching elevates the ambient (overall) concentration of nitrates in the groundwater but may have a greater or smaller impact on nitrate levels at wells used to supply drinking water. Basing damages to drinking water on leaching from agricultural production implicitly ignores the location of the production with respect to the well. As a consequence, a farm's production activities may have substantial effects on a well due to its proximity to the well, even though its effect on overall ambient quality is no different from any other farm's production in the area.

Determining well contamination levels requires incorporating the geologic and hydrologic data of an aquifer into the model. Hydrogeologic characteristics and groundwater flow of the aquifer determine how nitrates will affect various wells once in the groundwater. A tradable permit scheme which incorporates this type of data would allow permits to be traded based on final well contamination levels rather than on initial nitrate leaching levels.

The two forms of environmental regulation to be discussed in this paper are direct regulation, referred to as *command-and-control* (CAC), and permit trading. Direct regulation is simply a uniform abatement agricultural practice that meets the nitrate standard at wells imposed on all farms in the community by a regulatory authority. Permit trading, on the other hand, relaxes the homogeneity constraint and allows farms in the community to trade permits to achieve the same standard.

Economist have long argued that incentive-based mechanisms, such as the marketable permit system, are more efficient than direct regulatory approaches. These arguments are based on the assumption that a marketable permit system can achieve the same environmental quality standard as direct regulation, but at a lower cost, since polluters have flexibility in how they go about achieving the specified emission target. The empirical evidence for air pollution suggests that permit systems have the potential to generate large cost savings while inducing significant reductions in air pollutants as compared to standards (e.g., Atkinson and Lewis; McGartland and Oates).

In order to evaluate the effectiveness of the CAC and permit-trading regimes at controlling nitrate contamination of groundwater, the link from surface application of nitrogen to nitrates at a targeted well needs to be established.

While it is conceptually easy to monitor nitrate accumulation at a targeted well, it is much more difficult to model the physical processes that deliver those nitrates to the well. However, if groundwater regulatory policies are to be constructive in controlling nitrates it is important to be able to predict how much of the nitrogen applied on the surface leaches into groundwater and the subsequent transport and accumulation at the well.

Models

This section describes the production, soil and groundwater models used to make the connection between agricultural production and nitrate levels at a well. In order to evaluate the effectiveness of the regulatory models, farm level and regional data is needed to predict profits (and abatement costs) for production practices, nitrate leaching resulting from these production practices, transfer coefficients, and the accumulation of nitrates at groundwater wells. The integrated model used to complete this task is a composite of three distinct models: production, soil, and groundwater. Each model represents one level in the nitrate contamination process that results in nitrates at a targeted well.

The production model is designed to capture management responses, in terms of the choice of crop rotation and nitrogen fertilizer (N) application rate, to regulatory policies targeted at reducing leaching and, subsequently, nitrate levels in groundwater. Representative crop rotations and nitrogen management practices are portrayed in the production model. The crop rotation and the nitrogen applied to crops in this rotation are a production practice. The nitrates from these production practices may leach into the groundwater. To determine the level of leaching, the crop rotation and the nitrogen applied to crops in that rotation are entered into the soil model which predicts water and nitrogen leaching from the root zone. Results from the soil model for each production practice are then entered into the groundwater model which simulates nitrate movement and accumulation at the targeted well. The essence of the integrated model is provided in detail in the following three sections, one for each model.

Production Model

The production model should capture all production practices available to farms in a study area. There are numerous production practices available to farms, even within a single crop rotation, since many different rates of nitrogen can be applied to crops in that rotation. In the production model, profits would be established for the crop rotations. Important components of profits for the rotations are yields. Crop yield generally varies with nitrogen fertilizer. To capture the relationship between crop yield and N fertilizer, a crop-yield function can be estimated. Legumes, such as soybean and alfalfa, are often used as rotation crops. Because legumes fix their own nitrogen, they do not require fertilization. Yield estimates for these crops can be obtained from the soil model.

Profits vary by production practice as yields for the crops in rotation change. With regulation, the most profitable production practices may not be feasible for the area surrounding the well because nitrate leaching under these practices results in nitrate levels at the well exceeding the standard. In these cases the area may have to engage in less profitable production practices in order to meet the standard. The difference between the optimal production practice and a less profitable practice is the abatement cost associated with reducing nitrates at the targeted well.

Crop production under any of the production practices may involve contamination of the groundwater in the underlying aquifer by nitrate leaching from the root zone of the crop. Nitrate leaching varies by crop type, nitrogen application rate, weather, and soil characteristics. The soil model, which is discussed in the next section, can be used to predict nitrate leaching for each production practice.

Soil Model

The soil model described in this paper is the *Groundwater Loading Effects of Agricultural Management Systems* (GLEAMS) model, which simulates the hydrology, soil chemistry and crop growth of agricultural fields. The GLEAMS model is used to predict the fate of nitrogen in the root zone depending on agricultural management practices. Nitrogen in the root zone may be chemically transformed (mineralization, denitrification), taken up by the plant, leached from the root zone or remain in the profile. These processes are detailed in the nutrient component of GLEAMS.

GLEAMS divides the plant root zone effective for water and nutrient uptake into 3 to 12 layers, depending on the depth and thickness of the soil horizon. GLEAMS simulates nitrate movement through the soil profile by calculating nitrate transfer through each layer. Nitrates in the first (surface) layer are either lost to surface runoff or percolated down to the next layer. Runoff nitrate is a function of the nitrate concentration in the water and the runoff amount. Nitrates which percolate from any layer to an underlying layer depend on the nitrate concentration in that layer and the water percolated into the underlying layer.

GLEAMS also calculates other factors including nitrogen mineralization, immobilization, and nitrification[2], which can change the nitrate concentration in each layer. The model keeps track of nitrate mass in each layer. Percolated water and nitrates from the lowest layer are assumed to be the loadings to the groundwater from the root zone. A more detailed description of the GLEAMS model can be found in the user manual (Knisel).

The input for the GLEAMS model includes regional climate data such as precipitation, temperature, and solar radiation, in addition to crop and nitrogen management practices. Soil properties needed for the simulation include the silt, sand, and clay content of the soil, porosity, organic matter, and field capacity. The GLEAMS model should be validated by comparing predicted values with measured field data from an agricultural site. Once calibrated, GLEAMS can be used to predict nitrate loadings for different crops and nitrogen application rates.

Groundwater Model

The groundwater model described in this section is the U.S. Department of Defense Groundwater Modeling System (GMS), which simulates flow and contaminant transport in groundwater. The system was developed by the Engineering Computer Graphics Laboratory of Brigham Young University in cooperation with the U.S. Army Corps of Engineers Waterways Experiment Station. GMS is a comprehensive groundwater model which supports other existing industry models and provides for the sharing of information and data between different models.

GMS provides an interface to the groundwater flow model, MODFLOW, and the contaminant transport model, MT3D. MODFLOW is a three-dimensional, cell-centered, finite-difference, saturated-flow model capable of both steady-state and transient analyses. MT3D is a modular three-dimensional transport model that simulates contaminant advection, dispersion, and chemical reactions in groundwater[3]. MT3D is typically used in conjunction with a MODFLOW simulation. Flow values computed during a MODFLOW simulation are used by MT3D during the flow phase of the transport simulation. These two models, when put together, provide a comprehensive tool for examining groundwater flow and nitrate transport and accumulation.

A MODFLOW model can be constructed for a site to be studied. A detailed description of the site which includes the location of wells and pumping rates, the boundary of the domain to be modeled, recharge zones, and location of rivers and streams would be needed

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[2] Mineralization is the process where organic N is converted to inorganic N, the form used by crops, by bacteria in the soil. Immobilization is the process by which N is tied up by bacteria and not readily available for the plant. Nitrification is the conversion of ammonium nitrogen to nitrate nitrogen.

[3] The two main mechanisms that determine how a contaminant is transported in groundwater are advection and dispersion, where both processes depend strongly on groundwater flow. Advection is the process by which solutes are transported by the bulk flow of groundwater. There is also the tendency for the solute to spread out from the advective path. This spreading phenomenon is called dispersion (Freeze and Cherry).

for each of the layers of the aquifer. A three-dimensional grid can be created for the modeled area where each cell of the grid possesses a unique set of data used to calculate groundwater flow in the modeled area.

Two Forms of Environmental Regulation

Although the efficiency of the permit system has been acknowledged in theory and implemented as control for air pollution (Montgomery; Baumol and Oates), this paper is believed to be the first attempt to outline a method for implementing a marketable permit system as a groundwater pollution control strategy. The key to being able to conduct this analysis for groundwater pollution is establishing the physical relationship between (1) the surface application of nitrogen to a crop rotation (production) and nitrate leached into the groundwater (soil) and (2) the location of nitrogen leached and its contribution to the nitrate level at the targeted well (groundwater). The following sections discuss how these relationships are used to evaluate the effectiveness of direct regulation and permit trading for improving nitrate groundwater pollution.

To facilitate an understanding of the command-and-control and permit-trading regimes, a more formal statement of the pollution control problem in the context of agriculture production and groundwater is outlined in the following discussion. Assume that within the watershed there are m receptors (groundwater wells). The environmental quality standard for nitrates at receptor j is denoted q_j ($j = 1, \ldots, m$). Thus, the current environmental quality can be described by a vector $Q = (q_1, q_2, \ldots, q_m)$ whose elements indicate the concentration of nitrates at each receptor. Within the watershed there are k production practices available to n farms, where a production practice refers to a type of crop rotation and nitrogen fertilizer rate applied to crops in that rotation. All farms have the same set of production practices available to them. Soil types and, hence, nitrate leaching from these soils under each production practice are assumed to be identical across n farms. In other words, farms are assumed to be identical with respect to the available set of production practices and nitrate leaching into the groundwater from these practices. The farms are different because their locations relative to the well are different.

The dispersion of leachate (or nitrates) from each of the n farms is given by a $n \times m$ matrix D:

$$D = \begin{bmatrix} & \vdots & \\ \cdots & d_{ij} & \cdots \\ & \vdots & \end{bmatrix}$$

where d_{ij} represents the increase in the concentration of nitrates at receptor j from one unit of leachate, $e(k_i)$, from production practice, k, by farm i ($i = 1, \ldots n$). This matrix of transfer coefficients is given by the groundwater model. Because leaching is a function of the crop planted, nitrogen fertilizer applied, and rainfall, the rate of water and nitrate leaching may vary over time for each k. Furthermore, the nitrates leached into the groundwater may reach the well soon or it may take years, depending on the rate of groundwater flow. As a result, this matrix of transfer coefficients may change from year to year. The matrix described above is for a fixed interval in time,[4] dictated by the rate of nitrate leaching and groundwater flow. Hence, farm i's contribution to nitrates at well j from production practice, k_i, at this fixed time is equal to $d_{ij}e(k_i)$, where $e(k_i)$ is the nitrates leached from the soil into the groundwater from production practice k for farm i, which is predicted by the soil model.

The environmental authority of the region determines the set of standards which specify the maximum allowable contaminant level of nitrates at each receptor point: $Q^* = (q_1^*, q_2^*, \ldots, q_m^*)$. In the case of nitrates, the United States Environmental Protection Agency (EPA) has defined this amount as 10 parts per million (ppm) or less for public drinking water. The EPA standard of 10 ppm is taken as the standard at each receptor point for both the command-and-control (CAC) regime and per-

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[4] Because it may take years for nitrates to reach a well, a regulator may choose to target regulation for a future time period.

mit-trading regime. The next sections discuss first a command-and-control version of environmental regulation for groundwater and then add a competitive market for permit trading.

Command-and-Control Regime

Under a CAC regime, an environmental authority sets the nitrate standard at each receptor, Q*, at 10 ppm. It is assumed that the authority requires that each farm adopt the same production practice, k, so that the sum of nitrates across farms meets the standard of 10 ppm: $\Sigma_i d_{ij} e(k_i) \leq q_j^*$. In other words, the environmental agency specifies a uniform abatement production practice for all farms contributing nitrates to a well. This control program results in a specific vector of crop rotations and fertilizer application. In general these uniform CAC systems will require more control over the region than is required to limit the pollution to the desired level at the receptor, resulting in excessive costs.

Permit-Trading Regime

Montgomery was the first to formally analyze two systems of marketable pollution permits: a system of "pollution licenses", commonly referred to as an *ambient permit system* (APS), which confers the right to deliver pollutants to a receptor point, and a system of "emission licenses" referred to as an *emission permit system* (EPS) which grants the holder of the permit the right to emit pollutants up to a certain rate.

The permit-trading scheme to be examined in this study is the ambient permit system (APS) proposed by Montgomery. In this system, a permit grants the right to deliver a pollutant to a specific well. Each well has its own market in permits specific to that receptor. The goal is to achieve the predetermined standard at minimum abatement costs[5]. More formally, let $e(k_i)$ be the current rate of leaching from production practice, k, for farm i. If $AC(k_i)$ is the abatement cost associated with production practice k for farm i, then the social planner's problem under the APS is to find the vector of production practices, $K = (k_1, \ldots, k_n)$, that represents the solution to the following problem:

$$\text{minimize} \sum_i AC(k_i)$$

$$\text{s.t.} \quad E(K)D \leq Q^* \qquad E \geq 0.$$

where $E(K) = (e(k_1), \ldots e(k_n))$.

Farms are endowed with a finite number of permits or licenses, l_{ij}^{o}, which may be redeemed in the present period in exchange for the right to deliver one unit[6] of nitrate to a groundwater well. The permit market described in this paper is an auction market where the regulator, through an iterative process, finds the equilibrium permit price. The farms may trade these permits with one another at price p_j^*, the equilibrium price. Farm i can engage in trades as long as it does not deliver more nitrates to receptor j than it holds permits for: $d_{ij} e(k_i) \leq l_{ij}$, where l_{ij} denotes the number of permits held by farm i after trading has occurred.

Because permits are defined as the right to deliver one unit of nitrates to the well, trades occur on a one-to-one basis. However, each permit implies a different allowable nitrate loading rate (i.e., a different production practice) into the groundwater at each farm because of variations among the transfer coefficients. More specifically, farm i has to obtain $d_{ij} e(k_i)$ permits at each receptor j. The compliance cost of the APS to the farm is loss profits plus expenditure on permits, $p_j^*(l_{ij} - l_{ij}^{o})$. Expenditures on permits may be positive or negative because they can be bought or sold. That is, the cost of compliance to farm i, C_i, is

$$C_i = AC_i + p_j^*(l_{ij} - l_{ij}^{o})$$

where AC_i is the abatement cost incurred from switching from one production practice, k, to

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[5] Abatement cost is the loss in profits from choosing a less optimal production practice, k. It is assumed that switching a production practice is the only activity available to a farm to reduce nitrate leaching.

[6] Examples of some possible units are 1 ppm, 0.1 ppm, 0.01 ppm or 0.005 ppm.

another. If the farm sells permits, then $l_{ij} < l_{ij}^{o}$ and compliance costs are lower. For a farm which buys permits, $l_{ij} > l_{ij}^{o}$ and compliance costs are higher. The overall compliance cost of the permit market is $\Sigma_i C_i$.

Nitrate levels resulting from current (unregulated) production practices, with neither a permit nor command-and-control system included, will provide a means to evaluate the tradeoffs between gains occurring through different types of environmental policy interventions. Changes in farm profits, abatement costs, fertilizer application rates, leaching, and nitrate concentrations, in the overall groundwater and at individual wells, resulting from the introduction of the different regulatory schemes can be compared.

The Application

Before introducing a trading scheme at the farm level, several key components need to be determined. First, for any modeled area the wells and farms contributing nitrates to those wells would need to be identified. For purposes of discussion, suppose one well which is the drinking water source for several individuals is targeted in a watershed. The area surrounding this well is predominately farm land, consisting of only a few farms. The market in this case is small with just a few potential traders.

After identifying the well and farms, a planning horizon for the trading scheme must be selected. Historic climate data may be used to project future nitrate leaching for each production practice. The planning period selected must be sufficiently long to capture variations and extremes in weather, thereby demonstrating how year-to-year fluctuations in precipitation affect leaching and nitrate levels at the targeted well. For example, in drought years one might expect GLEAMS to predict little measurable leaching and GMS to show little change in nitrates in the groundwater for the weather conditions that occurred in these years. However, for an extremely wet year, one might expect GLEAMS to predict significant leaching and GMS to show higher nitrate levels in the groundwater. Furthermore, groundwater flow in aquifers is in general very slow, where it may take several years for nitrates entering the groundwater the first year of the simulation to reach the targeted well. The planning horizon should be sufficiently long to allow observation of nitrate movement and accumulation at the targeted well.

Since numerous production practices are available to farms and these practices may change year to year over the planning horizon depending on harvested crop prices and input prices, two additional simplifications can be made to the production model to make the analysis more manageable. The first is that the production practice initiated in year one by a farm does not change through the planning horizon. Fixing the production practice through time, however, does not fix nitrate leaching or nitrate movement or accumulation in groundwater (due to variability in rainfall). The second assumption is that profits (or abatement costs) do not change through time. Annual losses incurred from switching from a more profitable production practice to a less profitable one in year one is the same for each year of the planning horizon.

However, before introducing new nitrates into the groundwater, it is important to determine how nitrates already in the groundwater will impact the nitrate level at the well over the planning horizon. This provides a baseline for comparison in evaluating the effect of additional crop production over time. The next step is to evaluate how engaging in farming increases nitrate levels at the well over time. As the farming area produces, the nitrate level at the well may increase over time and could exceed 10 ppm at some point during the planning horizon. The goal of the regulatory schemes is to force farms to commit to a production practice at the start of the planning horizon to be continued for the length of the planning horizon so that the nitrate level at the well in the last year of the horizon is 10 ppm or less. Furthermore, nitrate levels at the well cannot exceed 10 ppm at any time over the planning horizon.

In order for farms to make decisions about abatement so that the standard is met under APS, transfer coefficients, marginal abatement costs, and initial permit allocations are needed. The transfer coefficient indicates the change in nitrate levels at the well from a change in nitrate leaching from a shift in production practices. Marginal abatement costs are defined as the change in abatement costs ($/acre) for a given change in nitrate levels (ppm) at the well resulting from a shift in the production practice. Marginal abatement costs are abatement costs for a production practice change divided by the transfer coefficient associated with that change. Farms are each given an initial endowment of permits at the start of the planning horizon[7]. They can trade with one another at the equilibrium price, p*, and this trade can take place as long as each farm has enough permits to cover its contribution to nitrates at the well after the trade. Each farm would compare its marginal abatement cost to p* when making decisions about abatement and permit trading. The process to find p* is discussed in the next section.

The Trading Scheme

The regulator sets up a web page that reports the amount delivered to the well for each farm under each production practice. Each farm has access to its $d_{ij}e(k_i)$. Assuming an initial distribution of permits, permit trading is allowed within the farming area. Each permit may be redeemed in year one of the planning horizon in exchange for the right to deliver 0.01 ppm of nitrate to the targeted well in the last year under the production practice chosen for the planning horizon. Each farm is a price taker in the permit market; that is, it is assumed no strategic behavior occurs in the market.

On this web page an auctioneer posts a permit price, p. Each farm knows its marginal abatement cost from switching from one production practice to another and the amount of nitrates at the well resulting from that practice. Based on the posted permit price, each farm must make a decision about which production practice to adopt for the planning horizon and the number of permits to buy or sell based on its contribution to the nitrate concentration at the well under that production practice. If the price of the permit is greater than the marginal abatement cost associated with switching from the most profitable production practice to a less profitable production practice for a farm, then the farm would abate (switch) and sell permits. If the price of the permit is less than the cost of switching, then the farm would not abate and would instead buy permits to cover its contribution to the nitrate concentration at the well under its optimal production practice.

Each farm logs onto the web page in March of year one, before planting, and submits its optimal production practice and the number of permits to trade based on the price posted by the auctioneer. The auctioneer requires two constraints to be satisfied under all the production practices and permits submitted by the farms. The first is that the nitrate concentration at the well does not exceed 10 ppm at any point over the planning horizon for the farming area under the production practices. If the production practices for the farming area result in a nitrate concentration at the well that complies with the standard, then the second requirement is that the market for permits clears. That is, the supply of permits equals the demand for permits. The optimal production practice for all farms is taken as the trading baseline. In other words, farms that reduce nitrogen leaching further control more than is required and will have permits to sell to other farms. Recall that a permit gives the holder the right to deliver 0.01 ppm of nitrates to the well, and these permits are traded at the beginning of the planning horizon based on nitrates delivered to the well the last year of the planning horizon.

GLEAMS calculates nitrate leaching and GMS calculates the subsequent nitrate level at the well under each production practice requested by the farms and for the farming area as a whole. The results of this round of the iteration are posted on the web page. If the

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[7] The initial distribution of permits among farms will not affect the cost-effectiveness of the permit system to the farming area as long as the permit market is competitive (Montgomery). However, the initial distribution is important because it will affect the level of compliance costs faced by each farm in the farming area. We assume that a politically feasible distribution of permits will be chosen.

nitrate level at the well exceeds 10 ppm at any point over the planning horizon, the auctioneer posts another permit price. If the standard at the well is met under the combination of production practices but the permit market does not clear, the auctioneer posts a higher price if there is excess demand or a lower price if there is excess supply in the permit market.

Farms submit another production practice and permits to trade, which may or may not be different from its predecessor, depending on the posted price. This procedure continues until farms submit a set of production practices that achieves the standard of 10 ppm at the last year of the planning horizon for the farming area, without exceeding 10 ppm at any point over the horizon and the market for permits clears. It is assumed that farms do not behave strategically when choosing a production practice; that is, farms do not make side payments to other farms nor do they act collectively against other farms. Through this iterative process a solution can be found. This optimal solution would consist of an allocation of production practices defining the optimal production practices chosen by each farm affecting the well at the market-clearing permit price, p*. At this price some farms would choose to sell permits while others would choose to buy them.

Under the CAC regime the abatement cost (compliance cost) is the same for each farm in the area (because the production practice is uniform across the area). Under the APS, abatement costs would be the greatest to those farms whose nitrates really count at the well (i.e., location matters). The farms closest to the well have lower marginal abatement costs and have the incentive to sell permits. The cost of compliance may be offset by selling permits to farms farther away, who have higher marginal abatement costs.

The total compliance cost associated with the post-trade allocation would be determined, and this cost would be compared to the cost of the CAC regime to determine the potential cost savings generated by permit trading at the market-clearing price. The difference between the total compliance costs of the two regimes would be the total cost savings. As studies in the air pollution literature have shown, the permit-trading system is more cost efficient compared to the CAC regime. If the cost savings of the permit system prove to be quite large relative the CAC regime in the case of groundwater pollution, then an APS can be an efficient strategy for reducing nitrate contamination of groundwater resulting from agricultural practices.

Conclusions

While applying N may increase crop yield within a crop rotation, and a farm's profits, it may also result in an increase in nitrates leached into the groundwater and subsequent nitrate accumulation at a well. An increase in nitrates in wells may lower drinking water quality and thereby impose health risks to current and future consumers of this well water. To ensure that the nitrate standard at the well is achieved year after year, regulation may be needed to encourage farms to adopt production practices that limit leaching and nitrate accumulation in groundwater and at wells. The objective of this paper was to describe two regulatory policies, specifically a permit market scheme and the benchmark command-and-control scheme, for controlling nitrate levels at a well at the farm level.

The costs imposed by the alternative forms of environmental regulation on the farms would depend upon the production practice adopted by a farm, location of that farm with respect to the well, and the direction and rate of groundwater flow. Different assumptions concerning production practices can be used to evaluate the performance of the CAC and APS in terms of cost savings. The CAC system requires that each farm adopt the same production practice so that the nitrate standard at the well at the end of the planning horizon is achieved. The APS accounts for information on transfer coefficients which indicates how the nitrate contribution to the well differs by a farm's location relative to the well. Given the price of an ambient permit each farm would choose a production practice so that the total nitrate contribution by the farming area, with each farm adopting its optimal practice at that price, would not exceed 10 ppm over the planning horizon and the permit market clears.

Three distinct models—production, soil and groundwater—are used to establish the connection between nitrogen applied on the surface to nitrates at the well. Each model represents one step in the process that leads to nitrates at the well. In the production model each farm adopts a production practice—crop rotation and nitrogen application rate. The production practice is entered into GLEAMS, which predicts water percolation and the level of nitrates leached. Predicted water and nitrates leached for each production practice are entered into the MODFLOW and MT3D interfaces of GMS, respectively. The groundwater simulations indicate the nitrate contribution at the well. This methodology converts the contamination problem from a nonpoint source to a point-source problem, and illustrates the importance of incorporating tools from other disciplines to initiate new avenues of economic research on the problem of groundwater contamination from agricultural production. With these tools a regulator is equipped to determine the ambient nitrate level in groundwater and the nitrate level at wells resulting from agricultural production practices.

References

Atkinson, S.E. and D.H. Lewis. "A Cost-Effective Analysis of Alternative Air Quality Control Strategies." *Journal of Environmental Economics and Management* 1(1974): 237–50.

Baumol, W.J. and W.E. Oates. *The Theory of Environmental Policy, Second Edition.* New York: Cambridge University Press, 1988.

Brady, Nyle. *The Nature and Properties of Soils, Ninth Edition.* MacMillan Publishing Company: New York. 1984.

Engineering Computer Graphics Laboratory, Brigham Young University. *GMS, Department of Defense, Groundwater Modeling System,* Version 1.1, 1995.

Environmental Protection Agency. *Another Look: National Survey of Pesticides in Drinking Water Wells: Phase II Report.* EPA 579/09-91-020, January 1992.

Fleming, Ronald A. The Economics of Agricultural Groundwater Quality: Effects of Spatial and Temporal Variability on Policy Design." Ph.D. Thesis, Oregon State University, 1995.

Freeze, R.A., and John Cherry. *Groundwater.* Prentice-Hall: New Jersey. 1979.

Knisel, W.G., ed. *GLEAMS, Groundwater Loading Effects of Agricultural Management Systems,* Version 2.10, UGA-CPES-BAED, Publication No. 5, 1993.

Mapp, H.P., D.J. Bernardo, G.J. Sabbagh, S. Geleta, and K.B. Watkins. "Economic and Environmental Impacts of Limiting Nitrogen Use to Protect Water Quality: A Stochastic Regional Analysis." *American Journal of Agricultural Economics* 76(November 1994): 889–903.

McGartland, A. M. and W.E. Oates. "Marketable Permits for the Prevention of Environmental Deterioration." *Journal of Environmental Economics and Management* 12(1985): 207–228.

Montgomery, W. David. *Markets in Licenses and Efficient Pollution Control Programs." Journal of Economic Theory* 5(1972): 395–418.

O'Leary, Mike, George Rehm, and Michael Schmitt. "Understanding Nitrogen in Soils." Minnesota Extension Service, University of Minnesota, FO-3770-C, 1994.

O'Neil, William B. and Robert S. Raucher. "The Costs of Groundwater Contamination." *Journal of Soil and Water Conservation* 45(1990): 180–183.

Pan, J.H., and I. Hodge. "Land Use Permits as an Alternative To Fertilizer and Leaching Taxes for the Control of Nitrate Pollution." *Journal of Agricultural Economics* 45(1994): 102–112.

Thomas, A. *The Bioeconomics of Regulation Nitrates in Groundwater from Agricultural Production: Comparing Taxes, Quantity Restrictions, and Pollution Permits.* Unpublished Ph.D. Thesis, Cornell University, August 1994.

Wall, Dave. "Nitrate in Groundwater–Existing Conditions and Trends." *Nitrogen in Minnesota Groundwater,* prepared for the Legislative Water Commission, December, 1991.