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Determining Socially Optimal Nitrogen Application Rates Using a Delayed Response Model: The Case of Irrigated Corn in Western Kansas

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Nitrate contamination of groundwater is an important problem. The transport of leached nitrate from the root zone to groundwater takes approximately 30 to 60 years. Many previous studies ignore this time lag by assuming instantaneous contamination. This analysis applies a delayed response model to account for the time lag between nitrogen fertilizer applications to the time the leached nitrate reaches groundwater. Results show that accounting for the leached nitrate externality reduces the nitrogen application rate by 13% and the returns above variable costs by 8% for farmers who apply both nitrogen and phosphorus. For farmers who do not use phosphorus, nitrogen use is reduced by 14% and the returns above variable costs by 22%. The application of phosphorous increased returns by more than 100% and significantly reduced leached nitrate.

Key words: delayed response model, groundwater contamination, irrigated corn, nitrate contamination

Introduction

In recent years there has been increasing public concern about drinking water contamination in the U.S., resulting in a rising demand for bottled water. From 1976 to 1988, consumption increased threefold, with Americans spending about $2 billion per year on bottled water (Castleman). Based on the U.S. Environmental Agency's (EPA's) 1996 national water quality inventory report to Congress, agriculture is believed to be the largest contributor to nonpoint source pollution of groundwater in the U.S. (U.S. EPA 1998). In an investigation of agricultural resources and environmental indicators over the period 1996–97, the USDA's Economic Research Service (ERS) reported that approximately 90% of 49 states identified agriculture as the major source of groundwater quality impairment (USDA/ERS 1997). Agriculture is also believed to be the leading source of quality impairment occurring in rivers and lakes (U.S. EPA 1998).

Nitrate-nitrogen (NO_3-N) from nitrogenous fertilizers is a major groundwater pollutant in the U.S. In Kansas, the problem of groundwater contamination by nitrate is especially significant, since Kansas relies more heavily on groundwater than any other state in the continental U.S. Roughly 51% of 2.3 million Kansans depend on groundwater for drinking,

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irrigation, and/or industrial use (Buchanan and Buddemeier). A 1996 survey of 833 public water supply systems in Kansas showed that 4% of the systems serving 1.3% of the Kansas population were contaminated with nitrates above the EPA's maximum contaminant level (MCL) of 10 parts per million (ppm) (Kansas Department of Health and Environment, pp. 7–8). Burkart and Kolpin's survey of wells in midwestern and northern states found that nitrate contamination of groundwater is greater in areas using irrigation, as is the case in western Kansas.

Fertilizer recommendations in the Great Plains are based on yield goals and nitrate concentration in the soil profile before planting (Vanotti and Bundy 1994a, b). While some studies indicate the need to use soil profile nitrate to determine nitrogen fertilizer recommendations, they do not incorporate the social cost of nitrate contamination in determining the socially optimal nitrogen application rates (e.g., Vanotti and Bundy 1994b; Schlegel, Dhuyvetter, and Havlin).

The objective of this study is to account for the possible leaching of nitrogen in determining socially optimal nitrogen application rates. Leached nitrate does not reach groundwater instantaneously after fertilizer use. Hence, there is a time lag between the accrual of benefits of fertilizer use by farmers to the time the resulting externality is felt by the society using the contaminated groundwater. Likewise, the effect of regulatory policies for controlling groundwater nitrate contamination is not immediate. Failure to account for the time lag of the effect of nitrogen application on water quality may lead to design of water quality policies that overregulate nitrogen fertilizer use (Kim, Hostetler, and Amacher).

Our study uses a delayed response model to determine the socially optimal nitrogen application rates for irrigated corn in western Kansas. This research expands on the 1996 work of Schlegel, Dhuyvetter, and Havlin, who conducted a fertilizer experiment spanning 30 years to determine the optimal level of nitrogen for irrigated corn in western Kansas. While this earlier study did not consider the social costs of nitrates being leached into groundwater, our model takes into account the time lag from when nitrogenous fertilizers are applied to the time when leached nitrates reach groundwater. Our delayed response model also incorporates the maximum contaminant level that is set by regulators.

The Model

Nitrate is a stock pollutant, i.e., it accumulates and degrades over time. A number of factors influence the transport of nitrates from the unsaturated zone into groundwater. Among these are precipitation and climate in general, soil type, subsurface geology, land use and management strategies, and the intensity of nitrogen use (Keeney). Because multiple factors impact nitrate transportation into groundwater, it is it difficult to formulate a tractable nitrate transport model. However, Conrad and Olson modeled mass transport of aldicarb (a stock pollutant with characteristics similar to nitrates) using a number of simplifying assumptions. Following Conrad and Olson, the change in total contamination of groundwater by nitrate at time t is given by:

$$(1) \qquad \dot{C}_t = (1 - \gamma)\eta N_{t-k} - \delta C_t, \quad \forall\, 0 \le k < t,$$

where C_t is the concentration of nitrate in groundwater at time t, γ is the rate of nitrogen loss due to volatilization and runoff, N_{t-k} is the nitrogen applied (lbs./acre) at time $t - k$,

k is the time lag in years which measures the delay from fertilizer application to the time the leached nitrate actually reaches groundwater, η is the proportion of applied nitrogen that is converted into nitrate pollutant, and δ is the degradation rate of nitrate in the groundwater due to denitrification. Equation (1) is linear and can be empirically estimated by ordinary least squares (OLS) methods when appropriate data are available.

A dynamic profit function that takes into consideration the externality of nitrate contamination may be estimated using equation (1) to characterize the dynamics of nitrate pollution. However, a damage function for nitrate contamination is required to enter the profit function as a cost to producers. Following Conrad and Olson, a quadratic cost function for nitrate contamination is used in this analysis. A quadratic function implies that the negative effect of the pollutant increases with an increase in its concentration. We assume that society's goal is to manage the contamination of groundwater.

It is important to consider the time lag (k) between application of nitrogenous fertilizer and entrance of leached nitrate into groundwater. Kim, Hostetler, and Amacher demonstrate that if the time lag of nitrate transport is ignored, too much pollution results—even at higher fertilizer taxes. The time lag complicates the management of fertilizer application because the impact of such management on nitrate concentration in groundwater (C_t) is felt $t+k$ years later.

The time lag from when nitrogenous fertilizers are applied to when the concentration of nitrate is detected in groundwater divides the modeling of nitrate stock level into two time periods: $0 < t_1 < k$, and $k \leq t_2 < T$, where T is the terminal period. Hence, the maximization problem can be solved recursively in two stages, one for each time period (t_1 and t_2). Each stage has a state equation for C_t (Kim, Hostetler, and Amacher). This model is called a delayed response model because the externality created by nitrogen application does not occur immediately.

It is assumed that the appropriate objective is to maximize farm profit (π) in stages 1 and 2 subject to nitrate contamination restrictions. The nitrate contamination is modeled using state equations in both stages, initial nitrate concentration (C_0) and the final nitrate concentration (C_T) in groundwater. Formally, this model is specified as follows:

$$(2)\qquad \underset{\{N,h\}}{\text{Max}}\ \pi = \int_0^k e^{-rt}\left[p\left(a + bN(t) - dN(t)^2\right) - fN(t) - \mathbf{w}'\mathbf{h}(t) - \theta C(t)^2\right]dt + \int_{t>k}^{T} e^{-rt}\left[p\left(a + bN(t) - dN(t)^2\right) - fN(t) - \mathbf{w}'\mathbf{h}(t) - \theta C(t)^2\right]dt,$$

subject to nitrate concentration growth in groundwater [(3) and (4)]:

$$(3)\qquad \dot{C}_t = (1-\gamma)\eta N(0) - \delta C(t), \qquad \forall\, 0 \leq k < t,$$

$$(4)\qquad \dot{C}_t = (1-\gamma)\eta N_{t-k} - \delta C(t), \qquad \forall\, k \leq t < T;$$

and initial and terminal conditions (5):

$$(5)\qquad C_0 < MCL \quad \text{and} \quad C_T \leq MCL.$$

In (2)–(5) above, r is the discount rate; a, b, and d are constants of the quadratic production function; p is the constant price of corn; $\mathbf{h}(t)$ is a vector of quantities of inputs other than nitrogenous fertilizers; **w** is a vector of constant prices for **h**(t); f is the constant price of nitrogen; θ is the damage coefficient; and *MCL* is the maximum contaminant level set by regulators. Other notations are as previously defined. Schlegel, Dhuyvetter, and Havlin used a quadratic corn production function, and that same function is employed here to facilitate comparison.[1]

Empirical estimation of θ is problematic, because data relating the N application rate with the consequent social damage of nitrates are unavailable. However, we can solve for θ at the steady-state equilibrium and then estimate empirically. Consider the general representation of equations (2)–(4):

$$\text{(6)} \qquad \text{Max } \pi = \int_0^\infty e^{-rt} B(N_t, C_t)\,dt,$$

$$\text{s.t.: } \dot{N}_t = 0,$$

$$\dot{C}_t = (1 - \gamma)\eta N_{t-k} - \delta C_t,$$

where B is the farm profit, which is a function of available nitrogen and nitrate concentration. Other notations are as defined in equations (1)–(5). The associated Hamiltonian is:

$$\text{(7)} \qquad H(N_t, C_t) = B(N_t, C_t)e^{-rt} + \lambda_t[(1 - \gamma)\eta N_{t-k} - \delta C_t]e^{-rt}.$$

After adjusting for time, the first-order conditions of equation (7), which are conditions for a maximum Hamiltonian, are as follows:

$$\text{(8)} \qquad H_N = B_N + \lambda_{t+k}(1 - \gamma)\eta e^{-rk} = 0; \;\; t \geq k.$$

The change in nitrate concentration due to current application of a unit of nitrogen is $(1 - \gamma)\eta$. However, this change is not realized until after time $t + k$, because nitrate resides in the vadose zone[2] for a period of time before actual contamination occurs. Therefore, the cost of contamination in time $t + k$ is discounted to the current period, i.e., $\lambda_{t+k}(1 - \gamma)\eta e^{-rk}$. The maximum condition for the time derivative of λ_t is expressed as:

$$\text{(9)} \qquad \dot{\lambda}_t = r\lambda_t - H_C \Rightarrow \dot{\lambda}_t = r\lambda_t - B_C + \lambda_t\delta.$$

Solving for λ_t from equation (8) after adjusting time by k years yields:

$$\text{(10)} \qquad \lambda_t = -\frac{B_N e^{rk}}{(1 - \gamma)\eta}.$$

Equating the time derivatives of equation (9) with equation (10) after eliminating λ_t gives:

$$\text{(11)} \qquad \dot{\lambda}_t = -\frac{(B_{NN}\dot{N}_{t-k} + B_{NC}\dot{C}_{t-k})e^{rk}}{(1 - \gamma)\eta} = -\frac{B_N e^{rk}(r + \delta)}{(1 - \gamma)\eta} - B_C.$$

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[1] Llewelyn and Featherstone observed that the Mitscherlich-Baule was the model of choice for irrigated corn in western Kansas. Due to lack of data on rate of irrigation, this model was not used in our study.

[2] The vadose zone is the area between the crop root zone and the water table.

Solving for $\dot{N}_t$ after advancing the system k years, and assuming $\dot{\lambda} = \dot{C} = 0$, gives:

$$\dot{N}_t = \frac{(r + \delta)B_N + B_C(1 - \gamma)\eta e^{-rk}}{B_{NN}}. \tag{12}$$

The derivatives B_N, B_C, and B_{NN} are obtained from the quadratic production function specified in equation (2). Assuming that $\gamma = 0$, and that the travel time of nitrate from the root zone to the vadose zone is within one year, equation (12) results in:

$$(r + \delta)\big(p(2dN_t - b) + f\big) + 2\theta\eta C_t = 0 \tag{13}$$

when $\dot{N}_t = 0$ (steady-state equilibrium). Solving for N_t from equation (13),

$$N_t = (pb - f)/2dp - (\theta\eta C_t)/(dp(r + \delta)). \tag{14}$$

Also, from equation (6), note that:

$$N_t = \delta C_t/\eta \text{ when } \dot{C}_t = 0. \tag{15}$$

Equating equations (14) and (15) and then solving for C^* results in:

$$C^* = \frac{\eta(r + \delta)(pb - f)}{2[\delta dp(r + \delta) + \theta\eta^2]}. \tag{16}$$

Rearranging equation (16) produces the following expression for the damage coefficient, θ:

$$\theta = \frac{\eta(r + \delta)(pb - f) - 2\delta dp(r + \delta)C_t^*}{2\eta^2 C_t^*}. \tag{17}$$

This damage coefficient represents the cost of nitrate contamination and is an important policy variable because it may be used to determine user fees that would induce farmers to internalize the nitrate pollution externality (Kim, Hostetler, and Amacher). The damage coefficient is positively related to output price, but is negatively related to nitrogen fertilizer price. This suggests that the level of θ should be evaluated based on output and nitrogen fertilizer prices.

It would be illuminating to compare the farm returns from the model that accounts for leached nitrate to the one that does not. Hence, an unconstrained farm profit model is estimated by omitting the nitrate pollution externality (implying the damage coefficient θ equals zero) and removing the constraint of $C_T \leq MCL$. Under this model, the unconstrained profit function is specified as:

$$\max_{\{N,h\}} \pi = \int_0^T e^{-rt}\big[\big(p(a + bN(t) - dN(t)^2\big) - fN(t) - \mathbf{w}'\mathbf{h}(t)\big]\,dt. \tag{18}$$

In later discussion, results from equations (2) and (18) are compared to determine the farm profit reduction due to accounting for the externality of groundwater contamination with nitrates.

Data

In their 1996 study, Schlegel, Dhuyvetter, and Havlin estimated a corn production function using data obtained from a long-term fertilizer trial at the Tribune, Kansas, Experiment Station. Nitrogen and phosphorus fertilizers were combined in a factorial experiment. Two levels of phosphorus (0 and 40 lbs./acre) were combined with six levels of nitrogen (0, 40, 80, 120, 160, and 200 lbs. of nitrogen per acre), giving 900 observations for each phosphorous level (30 years × 5 replications × 6 nitrogen levels). As noted earlier, to facilitate comparison, the Schlegel, Duyvetter, and Havlin corn production function is used in our analysis. Table 1 reports the estimated OLS coefficients as well as the assumed prices and costs of production used in this research.

Previous work found that the time lag between applications of nitrogen fertilizer and actual contamination of groundwater by the resulting nitrate is between 30–60 years in southern California (Pratt) and 20 years in Buffalo, Nebraska (Bentall). Soils in most of the midwestern states were formed in a similar manner. Hallberg estimated that the impact of excess application of nitrogen is reflected into groundwater in 30–40 years in midwestern states. In our investigation, the travel time of nitrate from the vadose zone to groundwater was assumed to be 35 years (the median of the range given by Hallberg).

Data on nitrates, which actually leach into groundwater from a given farm, are difficult to obtain. However, we adopt Yadav's premise that keeping the concentration of nitrate in the vadose zone at 10 ppm or less on a water basis results in a concentration of nitrate in groundwater which does not exceed 10 ppm. The MCL of 10 ppm of nitrate on a water basis is equivalent to about 50 lbs. of nitrate per acre-foot of soil (soil basis).[3] Thus, the soil basis amount of nitrate in the vadose zone is the constraint imposed on the profit-maximization problem; i.e., the concentration of nitrate in the soil vadose should not exceed 50 lbs./acre-foot of soil at any given time. The travel time from the root to the vadose zone, which represents the groundwater zone in this formulation, is expected to be within one year. However, the k value used is the estimated travel time of nitrate from the vadose zone to groundwater, i.e., $k = 35$ years. This arrangement ensures that the damage cost, which is based on the damage coefficient θ, is assessed to producers according to the actual time lag of nitrate pollution.

Due to lack of data, we initially assume that $\gamma = 0$, implying no loss of nitrogen by volatilization and runoff. From the above discussion and assumptions, the empirical model for estimating equation (4) is specified as:

$$(19) \qquad C_{t+1} = \eta N_t + (1 - \delta)C_t, \quad t \geq k = 0.$$

An OLS method was used to estimate coefficients for equation (19), using soil profile nitrate data collected by Hooker et al., and Schlegel, Dhuyvetter, and Havlin from a long-run fertilizer experiment at Tribune, Kansas. Since the use of phosphorus alters nitrogen use efficiency (Hooker et al.), two sets of coefficients for (19) were estimated,

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[3] Assuming 1 acre-foot of soil weighs 4 million lbs., the water content of soil at field capacity is 30%, the weight of 1 cubic foot of water is 62.4 lbs., and 1 acre is 43,560 square feet, then the volume of 1 acre-foot of water at field capacity level is 0.3 × 43,560 (or 13,068 cubic feet), and the weight of 1 acre-foot of water is 13,068 × 62.4 (or 815,443 lbs.). Thus we can convert nitrate concentration from a water basis to a soil basis for each 1 acre-foot depth based on the ratio of soil weight per acre-foot (4 million lbs.) to water weight per acre-foot (815,443 lbs.), or 4.905. This ratio indicates that 1 ppm of nitrate on a water basis is equal to approximately 4.905 on a soil basis. Therefore, 10 ppm of nitrate concentration in the vadose zone is equivalent to maintaining approximately 49.05 lbs. of nitrate per acre-foot of soil on a soil basis (Yadav, p. 117).

Table 1. The Estimated Corn Production Function, Price, and Cost Data Used in the Unconstrained Optimization Model

Parameter Estimates	With Phosphorus	Without Phosphorus
Constant	94.2716 (56.92)	70.7998 (31.22)
Nitrogen (N)	1.1007 (35.16)	0.7416 (17.30)
N^2	-0.0033 (-21.70)	-0.0023 (-11.38)
R^2	0.65	0.43
Prices and Costs:		
Corn price (p), \$/bushel	2.62	2.62
Cost of N fertilizer (f), \$/lb. of N	0.17	0.17
Production cost (W)[a], \$/acre	200.00	178.00

Sources: Schlegel, Dhuyvetter, and Havlin; Langemeier et al.; Sartwelle and Henson.
Note: Numbers in parentheses are asymptotic t-values of the corresponding coefficient.
[a] Production cost is total variable cost other than cost for N fertilizer per acre (includes cost for phosphorus application).

one set with phosphorus application and another without. Following are the regression results of equation (19), with the associated t-statistics in parentheses:

(20) With Phosphorus:
$$C_{t+1} = \underset{(2.65)}{0.14N_t} + \underset{(3.08)}{0.7C_t}$$
$$N = 48,\ R^2 = 0.85$$

and

(21) Without Phosphorus:
$$C_{t+1} = \underset{(3.08)}{0.16N_t} + \underset{(4.1)}{0.6C_t}$$
$$N = 48,\ R^2 = 0.91.$$

These results imply that for the with-phosphorus scenario, a unit increase in nitrogen applied increases nitrate in the vadose zone by 14%, i.e., $\eta = 0.14$. For the without-phosphorus scenario, $\eta = 0.16$, suggesting that a higher level of nitrate is leached beyond the root zone. Both Yadav and Viets obtained comparable figures.

The General Algebraic Modeling System (GAMS) program was used to estimate the nitrate-constrained profit-maximization problem [equations (2)–(5)] and the unconstrained problem [equation (18)]. The annual streams of benefits for both the constrained and unconstrained profit models were discounted using an annuity factor with a discount rate of 5%. A 5% discount rate is commonly used in groundwater quality literature (e.g., Conrad and Olson; Yadav and Wall).

Analysis was performed to examine the sensitivity of farm profit, optimal nitrogen, nitrate contamination levels, and the damage coefficient to estimated parameters from equations (20) and (21). The parameters analyzed were the proportion of applied nitrogen

Table 2. Nitrate Constrained and Unconstrained Profit, Optimal N, and Leached Nitrate at Steady-State Equilibrium: Irrigated Corn Production in Western Kansas

	With Phosphorus		Without Phosphorus	
Model	Annual Profit (\$/acre)[a]	Optimal N Applied (lbs./acre)	Annual Profit (\$/acre)[a]	Optimal N Applied (lbs./acre)
Unconstrained Optimization	357	159	125	145
Constrained Optimization	330	138	98	125

[a] Annual profit is based on average of 50-year present value of annuity (PVA):

$$PVA = \sum_{t=1}^{T} FV_t(1+r)^{-t}\left[\frac{r}{1-(1+r)^{-T}}\right],$$

where FV_t is future value of the stream of benefits net of variable costs for year t.

Table 3. Level of Nitrate After 30 Years (1961–1991) of Nitrogen Fertilizer Application

	Nitrate Level in Soil Profile (lbs./acre)			
	With Phosphorus (@ 40 lbs./acre)		Without Phosphorus	
Nitrogen Fertilizer Level (lbs./acre)	0–5 feet	5–10 feet	0–5 feet	5–10 feet
0	7.7	7.6	7.5	7.5
40	7.8	6.2	7.7	9.2
80	6.9	8.7	10.3	14.7
120	10.2	12.3	45.7	35.7
160	17.7	29.9	71.4	81.4
200	29.1	32.3	94.7	87.5

Source: Schlegel, Dhuyvetter, and Havlin.
Note: The nitrate levels were determined from soil samples taken in 1991.

converted into nitrate pollutant (η), rate of nitrogen loss due to volatilization and runoff (γ), proportion of nitrate that degrades in groundwater (δ), price of corn (p), price of nitrogen (f), the time lag (k), and the discount rate (r). Since no empirical data for nitrogen loss due to volatilization and runoff (γ) were available, a range of values was used to determine the sensitivity of profit, optimal application of nitrogen, optimal nitrate contamination level, and the damage coefficient to γ.

Results

As shown by data presented in table 2, farmers who apply phosphorus and desire to limit nitrates available for leaching would reduce nitrogenous fertilizer application by approximately 13% from the level of 159 lbs./acre (originally obtained by Nelson and Dhuyvetter and adopted in Schlegel, Dhuyvetter, and Havlin) to a level of 138 lbs./acre.

This reduction in fertilizer results in an 8% decrease in the annual returns above variable costs, from \$357 to \$330 per acre. For farmers who do not use phosphorus, accounting for the externality of nitrogenous fertilizer application leads to a 14% reduction in fertilizer (from 145 to 125 lbs./acre) and a 22% decline in profit (from \$125 to \$98 per acre).

The nitrate constrained and unconstrained model results also show that use of phosphorus increases per acre returns above variable costs by more than 100%. The difference in returns between the with- and without-phosphorus scenarios suggests that soils in the study area are phosphorus deficient. Hence, an overwhelming incentive exists for farmers with phosphorus-deficient soils to apply phosphatic fertilizers to increase corn yield and returns above variable costs.

Phosphorus also reduces nitrate leaching, since it increases nitrogen use efficiency (Hooker et al.). Table 3 shows that the level of leached nitrate in the without-phosphorus plots is roughly three times the level found in the with-phosphorus plots for farmers who apply more than 150 lbs. of nitrogen per acre.[4] These findings underscore the importance of applying balanced nutrients to increase profit and environmental quality.

Table 4 reports the sensitivity of the nitrate-constrained farm profit, level of nitrate leached, and optimal nitrogen application at steady-state equilibrium to varying seven parameters by ±30% and ±67%. The nitrate MCL of 50 lbs./acre is a binding constraint over all reported values of proportion of nitrate that degrades in groundwater (δ), price of N (f), price of corn (p), contaminant transport time lag (k), and farmers' discount rate (r). The constraint is nonbinding if the value of proportion of applied nitrogen converted into nitrate pollutant (η) falls below 0.1. In actual situations, such values are unrealistic since nitrogen utilization efficiencies of more than 90% are rare in field conditions (Viets). MCL is also nonbinding when the proportion of applied nitrogen lost due to volatilization and runoff (γ) is 20% or greater.[5]

The optimal nitrogen level and farm returns for the nitrate-constrained model are sensitive to values of the proportion of nitrogen converted to nitrate pollutant (η), the loss of nitrogen due to volatilization and runoff (γ), and the degradation rate of nitrate (δ). Sensitivity to these parameters is due to their direct impact on the nitrate contaminant, C_t. For instance, in order to meet the MCL constraint, the use of highly soluble nitrogenous fertilizers increases η, implying a lower optimal level of nitrogen, and hence farm returns.

From table 4, an increase of η from 0.05 to the base value of 0.15 lowers the optimal nitrogen level from 159 lbs./acre to 137 lbs./acre for farmers who use phosphorus, and from 138 lbs./acre to 125 lbs./acre for farmers who do not use phosphorus. The corresponding constrained profit decreases by 6%, from \$352/acre to \$330/acre for farmers who use phosphorus. For farmers who do not use phosphorus, the constrained returns decrease by 15%, from \$115/acre to \$98/acre.

A decrease of nitrogen loss due to volatilization and runoff (γ) from 0.3 to 0.05 would lead to a 16% reduction of the optimal nitrogen, from 159 lbs./acre to 134 lbs./acre for farmers who use phosphorus. The corresponding farm returns would fall by 4%, from \$343/acre to \$330/acre. For farmers who do not use phosphorus, optimal nitrogen would

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[4] Nitrate is considered leached when it percolates beyond the root zone (0–5 feet for corn).

[5] It is safe to assume values of γ lower than 20%, i.e., that the MCL is binding. Freney, Simpson, and Denmead observed that 25% of ammonium nitrate was lost through volatilization when applied on soil surface without being incorporated. However, they noted that incorporation of ammonium nitrate in soil greatly reduced the rate of volatilization. In this study, ammonium nitrate was incorporated, and hence rate of volatilization is likely to be less than 20%.

Table 4. Sensitivity Analysis of the Nitrate Constrained Farm Profit, Nitrate Leaching, Optimal Nitrogen Application, and the Damage Coefficient to Parameter Changes

	Farm Profit[b] ($/acre)		NO_3-N Contamination[c] (lbs./acre)		Optimal Nitrogen Level[c] (lbs./acre)		Damage Coefficient, θ [$/(lb. of NO_3-N)^2]	
Parameter[a]	With Phos.	Without Phos.	With Phos.	Without Phos.	With Phos.	Without Phos.	With Phos.	Without Phos.
η = 0.05	352	115	25	21	159	138	0.77	0.85
0.10	344	110	49	40	159	138	0.20	0.22
0.15[d]	330	98	50	50	137	125	0.11	0.11
0.25	269	78	50	50	77	77	0.06	0.06
γ = 0.30	343	109	42	42	159	138	0.12	0.12
0.20	339	107	49	46	159	138	0.11	0.11
0.10	331	104	50	50	142	138	0.11	0.11
0.05	330	103	50	50	134	137	0.11	0.11
δ = 0.22	297	83	50	50	94	83	0.07	0.07
0.27	317	92	50	50	116	101	0.09	0.09
0.32[d]	330	98	50	50	138	125	0.11	0.11
0.42	338	105	50	50	159	138	0.15	0.15
f = 0.07	346	110	50	50	138	120	0.11	0.11
0.12	338	104	50	50	138	122	0.11	0.11
0.17[d]	330	98	50	50	138	125	0.11	0.11
0.27	316	86	50	50	138	126	0.11	0.11
p = 1.62	110	-26	50	49	138	127	0.07	0.07
2.12	220	35	50	50	138	127	0.09	0.09
2.62[d]	330	98	50	50	138	125	0.11	0.11
3.62	552	225	50	50	138	120	0.15	0.15
k = 25	329	98	50	50	138	125	0.11	0.11
30	329	98	50	50	138	125	0.11	0.11
35[d]	330	99	50	50	138	125	0.11	0.11
45	331	99	50	50	138	125	0.11	0.11
r = 0.02	565	177	50	50	138	126	0.10	0.10
0.05[d]	330	98	50	50	138	125	0.11	0.11
0.06	287	86	50	50	138	125	0.11	0.11
0.10	187	67	50	50	138	124	0.12	0.12

[a] Parameter definitions: η is the proportion of N applied that is turned into nitrate pollutant, γ is the rate of nitrogen loss due to volatilization and runoff, δ is the proportion of nitrogen that degrades in groundwater, f is the price of N ($/lb.), p is the price of corn ($/bushel), k is the lag time in years from time N is applied to time nitrate reaches groundwater, and r is the farmer's discount rate.

[b] Profit represents average of 50-year present value of annuity.

[c] Values are at steady-state equilibrium

[d] Denotes the base value of parameters used for computing social profits reported in table 2. There are two values of η (the proportion of N applied that is turned into nitrate pollutant). For the with-phosphorus case, η is 0.14, and η is 0.16 for the without-phosphorus case.

decrease by only 1%, from 138 lbs./acre to 137 lbs./acre, and the corresponding farm returns would decrease by 6%, from $109/acre to $103/acre.

The proportion of nitrogen that degrades into groundwater (δ) has a significant impact on returns and optimal nitrogen level. An increase of δ from 0.22 to the base value of 0.32 would increase the optimal nitrogen by 47%, from 94 lbs./acre to 138 lbs./acre for farmers who use phosphorus. The corresponding constrained farm returns would increase by 11%, from $297/acre to $330/acre. For farmers who do not use phosphorus, optimal nitrogen would increase by 51%, from 83 lbs./acre to 125 lbs./acre, resulting in an 18% increase in profit, from $83/acre to $98/acre. The sensitivity of optimal nitrogen to proportion of nitrogen which degrades in groundwater implies that development of a technology leading to fast degradation of nitrates in groundwater would allow for higher nitrogen fertilizer application rates, and hence profit, without compromising water quality.

The optimum nitrogen applied and nitrate contamination levels in both the with- and without-phosphorus application scenarios are robust across a wide range of values of price of nitrogen (f), corn price (p), the time lag of nitrate transport (k), and the farmers' discount rate (r). For all values of f, p, k, and r considered, optimum nitrogen for the with-phosphorus case is 138 lbs./acre, and between 120–127 lbs./acre for the without-phosphorus case. Changing the price of nitrogen fertilizer by about 300% (from $0.07/lb. to $0.27/lb.) would not change the optimum level of nitrogen applied for the with-phosphorus case. Similarly, increasing corn price by 123% (from $1.62/bushel to $3.62/bushel) would not change the nitrogen optimal level for the with-phosphorus case. For the without-phosphorus scenario, the optimum nitrogen application would decrease by only 6%, from 127 lbs./acre to 120 lbs./acre. These results imply that the optimal nitrogen application (N^*) and the nitrate resident in the vadose zone (C^*) obtained in this research apply to a wide range of input and output prices and discount rates. (Schlegel, Dhuyvetter, and Havlin also observed a robust optimum nitrogen application rate over a wide range of input and output prices.)

A change in the time lag of nitrate transport (k) from 25 years to 45 years does not alter the optimal nitrogen application of 138 lbs./acre for the with-phosphorus case or the 125 lbs./acre for the without-phosphorus scenario. Optimal nitrate contamination for both the with- and without-fertilizer scenarios also remains unchanged at 50 lbs./acre. The corresponding profits also remain fairly stable at about $330/acre for the with-phosphorus case, and $98/acre for the without-phosphorus case. Thus the results obtained apply across a fairly wide range of soil characteristics that influence nitrate transport, climatic conditions, and other factors affecting the travel time of nitrate pollutant from the root zone to groundwater.

An increase of the discount rate (r) from 0.02 to 0.10 does not change the optimum nitrogen level of 138 lbs./acre for farmers who use phosphorus. For farmers who do not use phosphorus, the optimum nitrogen changes only slightly, from 126 lbs./acre to 124 lbs./acre. A discount rate of 6% or higher reduces the farm returns to less than $300/acre, while a value of r equal to 2% increases returns to more than $500/acre.

The damage coefficient (θ) at the baseline values of parameters considered in the sensitivity analysis reported in table 4 is $0.11/(lb. of NO_3-N)^2 both for farmers who use phosphorus and those who do not. This implies that if regulators want farmers to internalize the externality of polluting groundwater with nitrates, they would assess a user fee of $0.11 per pound squared of leached nitrates. As shown in equation (17), the damage coefficient is a function of η, γ, δ, p, f, and MCL. However, comparative statics reported in table 4 show that η, δ, and p exert a significant influence on the damage coefficient. As is the case for farm returns, the optimal nitrogen application (N^*) and the nitrate contamination level (C^*) are highly influenced by the proportion of nitrogen applied converted to nitrates (η). A 100% increase in η from 0.05 to 0.10 leads to a 74% decrease in the damage coefficient from \$0.77/(lb. of NO_3-N)^2 to \$0.20/(lb. of NO_3-N)^2 for farmers who use phosphorus. For farmers who do not use phosphorus, the corresponding decrease in the damage coefficient is also 74%, from \$0.85/(lb. of NO_3-N)^2 to \$0.22/(lb. of NO_3-N)^2.

Conclusions and Implications

A delayed response model was used to determine the socially optimal level of nitrogen application in irrigated corn in western Kansas. The model indicated that the optimal nitrogen application rate would be reduced by 13% for farmers who use phosphorus and by 14% for farmers who do not use phosphorus when the effect of leached nitrate is taken into account. Our results suggest that reducing the nitrogen application rates currently used for irrigated corn in western Kansas can diminish nitrate contamination of groundwater within the region. The return above variable costs to the farmer is reduced when taking into account the effect of leached nitrates, with a reduction of 8% for farmers who use phosphorus and 22% for farmers who do not use phosphorus. At the baseline values of parameters, the damage coefficient equals \$0.11/(lb. of NO_3-N)^2 both for farmers who apply phosphorus and those who do not. This finding implies regulators may set user fees of \$0.11 per square pound of nitrate leachate found in the vadose zone of a farm.

Sensitivity analysis showed that returns, optimal nitrogen, leached nitrates, and the damage coefficient were robust across a wide range of values of the price of nitrogen, price of corn, the time lag of nitrate transport, and the farmer's discount rate. Thus the optimal nitrogen application rate (N^*) and nitrate resident in the vadose zone apply to a wide range of input and output prices. Results are sensitive to extreme values of the proportion of nitrogen converted to nitrate pollutant, proportion of nitrogen lost due to volatilization and runoff, and degradation rate of nitrate. Further research is needed to determine their values before making definitive fertilizer recommendations that account for groundwater contamination. Sensitivity of the results to the parameters reveals a need for flexible environmental regulations since agricultural production depends on physical climatic and biological environments, which can vary widely from one region or season to another.

The total irrigated corn acreage produced in Kansas during 1998 was 1.59 million acres (USDA 1999). If corn growers produce without accounting for nitrate leaching, they would realize per acre returns of \$357 above variable costs for the base case and \$330 if they account for nitrate leaching. Based on these figures, the potential impact of regulating nitrogen application to improve water quality in the state would result in a \$43 million reduction in income per year.

Given this rough estimate of lost income, it does not immediately appear that farmers have an incentive for reducing nitrogen application rates. Abler and Shortle identified four major strategies for reducing agrichemical pollution: economic incentives, regulatory standards, research and development, and moral suasion and education. Economic incentives include taxes or fees on polluting inputs, or subsidies for farmers who use pollution-reducing practices. Regulatory standards include mandatory regulations aimed at reducing agrichemical pollution. Both the federal and the state governments are increasingly using regulatory standards to compel the use of pollution-reducing practices by farmers (U.S. EPA 1993). Research and development is a long-term approach leading to development of production practices that reduce pollution. Finally, the moral suasion and education approach assumes that farmers would voluntarily reduce application of polluting inputs if they are made aware of the cost of the pollution externality of their inputs to society.

Bosch, Cook, and Fuglie evaluated the effectiveness of regulatory standards and a combination of incentives in Nebraska. They found that while regulation led to higher rates of adoption of nitrogen-reducing practices, it lacked an educational effort. Hence, polluters may not comply with the regulations if they can avoid being detected. The authors concluded that regulatory standards would be more effective if accompanied by education and persuasion (as did the U.S. General Accounting Office).

In a recent investigation of the role of education on the adoption of pollution-control practices, Ribaudo and Horan note that educational effectiveness depends on the presence of three key elements: (*a*) the action being promoted for improving water quality also assures increased farm profits, (*b*) the participating farmers have strong altruistic or stewardship motives, and (*c*) the cost of direct pollution of water used in the community is sufficiently large. All three of these conditions may not hold for the western Kansas irrigated corn situation described here. Consequently, the efforts of improving water quality using only educational programs may yield limited success.

Farmers may adopt some management practices for increasing nitrogen use efficiency, and hence reduce nitrate leaching and probably maintain yield levels. For example, applying nitrogen with phosphorus for P-deficient soils in western Kansas significantly reduces leached nitrate and increases returns by more than 100%. Other methods that may reduce leaching are the split application of nitrogen, planting scavenger crops, and use of nitrate inhibitors (NIs). Split application of nitrogen and the use of NIs are more effective in sandy soils than on finer soils (Hergert and Wiese; Maddux and Barnes). However, NI usage and split nitrogen applications reduce nitrate that leaches beyond the root zone. This implies the two methods may not have a significant impact on yield on a year-by-year basis. Nevertheless, if the benefit of reducing nitrate leaching over a long period is accounted for, employing those two methods may be beneficial.

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