ECONOMIC AND ENVIRONMENTAL BENEFITS OF SOIL/WATER NITROGEN TESTING: THE CASE OF CENTRAL NEBRASKA

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ABSTRACT

This research presents a competitive dynamic model to evaluate the economic and groundwater quality benefits resulting from the adoption of soil/water nitrogen testing. The model is applied to an irrigated corn production county in the Nebraska Mid-State area where the groundwater contamination level from nitrates is reported to be, on average, 18.7 parts per million (ppm). Adoption of nutrient management practices would result in increased economic benefits to farmers and reduced nitrate stocks in groundwater.

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Introduction

Nitrogen fertilizers applied by farmers have the potential to runoff into streams or ponds and to leach into groundwater, where their accumulation tends to degrade water quality for a variety of beneficial uses. It has been reported that fertilization efficiency associated with nitrogen fertilizer use ranged between 30 percent and 70 percent in U.S. crop production (Legg and Meisinger, 1982). A more recent study has reported that it ranges from 65 percent with a conventional furrow irrigation system to 85 percent with a center-pivot irrigation system in a continuous corn production area in Kansas (Williams et al., 1997).

A policy for managing groundwater quality that has been widely discussed in the literature is an accounting procedure associated with the voluntary adoption of nitrogen fertilizer management practices. Nitrogen fertilizer management practices discussed in these studies include testing for residual soil nitrogen in the root zone and for nitrates in groundwater used for irrigation. The accounting procedure credits nitrates in the soil and groundwater in deriving the recommended nitrogen application rate and is designed to increase economic efficiency by reducing nitrogen fertilizer use. However, recent studies report that the adoption of soil/water nitrogen testing resulted in increased yields (Fuglie and Bosch, 1995; Bosch, Cook, and Fuglie, 1995) which implies increased nitrogen fertilizer use.

The objective of this study is to estimate economic and environmental benefits resulting from the adoption of soil/water nitrogen testing. To achieve this goal, a competitive dynamic model associated with and without the voluntary adoption of nitrogen fertilizer management practices is presented. The model is then applied to a continuous corn production area in the Nebraska Mid-State area, where the groundwater nitrogen contamination level was reported to be 18.7 parts per million (ppm) on average during the period 1988-1990.

The Model

Most economists who have examined nonpoint-source groundwater pollution problems have assumed that both crop output and nonpoint-source pollution are jointly produced with the same application of nitrogen fertilizer. However, Kim, Sandretto, and Lee (KSL, 1999) have recently demonstrated that individual specification of crop output and nonpoint-source pollution production functions implies that the production processes are nonjoint in input quantities. Under the assumption of nonjointness in nitrogen fertilizer use, the crop production function is specified as a function of consumptive nitrogen fertilizer use rather than the amount of nitrogen fertilizer applied. This specification is also consistent with the fundamental assumption of production economics that all variable inputs are fully employed in the production process. However, Kim et al. (1997) and KSL (1999) have shown that

(1) $$B[\sigma n^*(t)] = \sigma B[n^*(t)] ,$$

where B represents economic benefits, σ is a fertilization efficiency coefficient, and n^* is the amount of nitrogen fertilizer applied, and therefore, σn^* represents the consumptive use of nitrogen fertilizer. Equation (1) indicates that the amount of nitrogen fertilizer lost through leaching and runoff does not contribute to economic benefits. Since it is more convenient to use the application rate rather than the rate of consumptive use of nitrogen fertilizer, the condition presented in equation (1) reduces the complexities associated with using consumptive nitrogen fertilizer use.

A quadratic crop production function has the advantage of generating a linear nitrogen fertilizer demand function, which is easily tractable mathematically. Furthermore, Berck and Helfand (1990) demonstrated that aggregate production functions for estimating crop response across large areas (fields or regions) with heterogeneity or nonuniformities in the distribution of inputs, such as nitrogen fertilizer and irrigation water, will result in smooth nonlinear functions that are concave with positive marginal products such as a quadratic function.

(A). Adoption of Nitrogen Fertilizer Management Practices and Its Effects on Nitrogen Fertilizer Use, Net Economic Benefits, and Groundwater Quality

When farmers adopt soil and water nitrogen testing, a crop production response to nitrogen fertilizer is then presented by:

(2) $$Y[n^i(t)+S^i(t)+w^iN^i(t)] = \alpha[n^i(t)+S^i(t)+w^iN^i(t)] - (1/2)\beta[n^i(t)+S^i(t)+w^iN^i(t)]^2,$$

where the superscript i represents the ith irrigation technology, S(t) is the amount of nitrates in the root zone area, w is the ratio of the amount of irrigation water use per acre to the amount of groundwater available per acre from the underlying aquifer, N(t) represents the nitrate stock in groundwater, therefore, wN(t) represents the amount of nitrates available from irrigation water, and α and β are positive constants. The derived nitrogen fertilizer demand function given the adoption of nitrogen fertilizer management practices is then represented by:

(3) $$P_n = P_y[\alpha - \beta S^i - \beta w^iN^i(t)] - P_y\beta n^i(t).$$

The area underneath the nitrogen fertilizer demand function described in equation (3) represents the economic benefits resulting only from nitrogen fertilizer use. To measure economic benefits resulting from use of both nitrogen fertilizer and residual nitrates available from the soil and contaminated groundwater, the nitrogen fertilizer demand function is then represented by:

(4) $P_n = P_y[\alpha - \beta n^*_i(t)]$,

where $n^*_i(t) = n^i(t)+S^i(t)+w^iN^i(t)$. Applying equation (1), net economic benefits (NB) resulting from nitrogen fertilizer use under nutrient management practices are then represented by:

(5) $$NB^i(t) = \sigma_i \int_0^{n^*_i(t)} P_y[\alpha - \beta x]\delta x - Cn^i$$

$$= \sigma_i P_y[\alpha n^*_i(t) - (1/2)\beta(n^*_i(t))^2] - Cn_i,$$

where x is a variable of integration and C is the unit cost of nitrogen fertilizer (dollars per nutrient pound).

For a given soil type and topography, the amount of nitrogen fertilizer lost through leaching depends largely on the adopted irrigation technology. Let the change in the stock of nitrates in groundwater, $\dot{N} = \partial N(t)/\partial t$, be represented by the following system of first-order differential equations:

(6) $$\dot{N}_i(t) = \tau_i[n^i(t) + S^i(t) + w^iN^i(t)] - \rho^iN^i(t) \quad \text{for } i = 1, 2, \ldots, m,$$

where τ_i represents the rate of nitrate leaching such that $\tau_i < (1-\sigma_i)$, and ρ_i represents the rate of nitrate discharge from the stock of nitrates in groundwater, which is the sum of natural nitrate discharge due to groundwater flows and the rate of artificial nitrate discharge through pumping groundwater for irrigation. Inserting equation (3) into equation (6), and then solving the resulting first-order differential equation results in the following:

$$(7)\qquad N^i(t) = \phi^i + (N_o - \phi^i)\exp(-\rho^i)t \qquad \text{for } i = 1, 2, \ldots, m,$$

where $\phi^i = [(\tau^i/\rho^i\beta)(\alpha\text{-}C/P_y)]$ and $N_o = N(t{=}o)$.

The time path of nitrogen fertilizer use is then obtained by inserting equation (7) into equation (3), and presented in equation (8).

$$(8)\qquad P_n = P_y\{\alpha - \beta S^i - \beta w^i[\phi^i + (N_o - \phi^i)\exp(-\rho^i)t]\} - P_y\beta n^i(t).$$

Finally, the present value of net economic benefits ($PVNB^i$) with the nutrient management practices are then represented by:

$$(9)\qquad PVNB^i = \int_0^\infty \exp(-rt)NB^i(t)\delta t,$$

where $NB^i(t)$ is as presented in equation (5).

(B). Effects on Nitrogen Fertilizer Use and Net Economic Benefits of Not Adopting Nutrient Management Practices

When farmers do not adopt nutrient management practices such as soil and water nitrogen testing, the crop production response to nitrogen fertilizer is then represented by:

$$(10)\qquad Y[n_j(t)] = \alpha n_j(t) - (1/2)\beta[n_j(t)]^2,$$

where $n_j(t)$ is the amount of nitrogen fertilizer application without nutrient management practices. The derived nitrogen fertilizer demand function estimated from the crop production function (10) is represented by:

$$(11)\qquad P_n = P_y[\alpha - \beta n_j(t)].$$

The area underneath this nitrogen fertilizer demand function represents the economic benefits resulting only from nitrogen fertilizer use. Farmers receive economic benefits from residual nitrates even if they do not adopt the nutrient management practices so that the necessary conditions for efficient use of nitrogen fertilizer are independent of the residual nitrates available from the soil and contaminated groundwater. Therefore, economic benefits resulting from nitrates use from all sources are represented by the area underneath the following nitrogen fertilizer demand function:

(12) $P_n = P_y[\alpha - \beta n^o_j(t)]$,

where $n^o_j(t) = n_j(t) + S_j(t) + w_jN_j(t)$. Net economic benefits (NB) resulting from nitrogen fertilizer use without adopting nutrient management practices are then represented by:

$$(13) \quad NB_j(t) = \sigma_j \int_0^{n^o_j(t)} P_y[\alpha - \beta x]\delta x - Cn_j(t)$$

$$= \sigma_j P_y[\alpha n^o_j(t) - (1/2)\sigma_j P_y \beta [n^o_j(t)]^2 - Cn_j(t),$$

where x is a variable of integration.

Changes in the nitrate stock in groundwater are then represented by the following first-order differential equation:

$$(14) \quad \dot{N}_j(t) = \tau_j[n_j(t) + S_j(t) + w_jN_j(t)] - \rho_jN_j(t) \quad \text{for } j = 1, 2, \ldots, m.$$

Inserting equation (11), at the unit cost of nitrogen fertilizer C, into equation (13) and then solving the resulting first-order differential equation results in the following:

$$(15) \quad N_j(t) = \phi_j + (N_o - \phi_j)\exp(-\rho_j+\tau_jw_j)t \qquad \text{for } j = 1, 2, \ldots, m,$$

where $\phi_j = \tau_j[(\alpha/\beta)-(C/P_y\beta)+S_j(t)]/[\rho_j-\tau_jw_j]$ and $N_o = N(t=o)$.

Inserting equation (15) into equation (13), the present value of net economic benefits ($PVNB_j$) without adopting the nutrient management practices are then represented as follows:

$$(16) \qquad PVNB_j = \int_0^\infty \exp(-rt)NB_j(t)\delta t.$$

By comparing the crop production function (2) associated with the nutrient management practices and the crop production function (10) without the nutrient management practices, it is clear that crop yield without the nutrient management practices would be higher. However, net economic benefits resulting from nitrates use with the nutrient management practices are greater than those without the nutrient management practices, because residual nitrates available from the soil and contaminated groundwater are incorporated into the profit maximization model for efficient nitrogen fertilizer use.

Application to Merrick County, Nebraska

The study area is located in Merrick County, Nebraska, where the observed nitrate concentration level in groundwater on average was 18.7 parts per million (ppm), according to a survey conducted by the Central Platte Natural Resources District (CPNRD) during the 1988-1990 period. Economic and geohydrologic data for the study area presented in Table 1 are from a previous study by Kim, Schaible, and Daberkow (1999). These authors obtained the hydrologic data from Bentall (1975a; 1975b); Exner and Spalding; Peckenpaugh and Dugan; and Signor et al. The irrigation efficiency coefficients data were obtained from Williams et al. Data on groundwater quality, groundwater pumping costs, the amounts of nitrogen fertilizer and irrigation water applied during the period between 1988 and 1990 were obtained from a survey conducted by the CPNRD. Data on prices for corn and soybeans are from various volumes of Agricultural Statistics, USDA. Nitrogen fertilizer price data are from Vroomen and Taylor.

The fertilization efficiency coefficient associated with the ith irrigation technology is assumed to be identical with its irrigation efficiency coefficient for two reasons. First, estimates of irrigation water and nitrogen fertilizer losses through runoff and leaching from the Erosion Productivity Impact Calculator (EPIC) simulation model were unreliable[1]. Second, since nitrates are highly soluble and deep percolation into the aquifer generally carries only soluble substances because the soil acts as a filter for the percolating water (Porter, et al.), the rate of fertilization efficiency is assumed to be the same as the rate of irrigation efficiency.

Economic data presented in Table 1 are also from previous studies for the Nebraska Mid-State area (KSL, 1999; Kim, Schaible, and Daberkow, l999). Since most acreage in the CPNRD is allocated to continuous corn production to meet local feed demand for livestock production, these studies employed a multiple inputs - single output normalized profit function (Huffman and Evanson; Shumway) to estimate the supply of corn, the demand for nitrogen fertilizers, and the demand for irrigation groundwater. Pooled data for the period 1960-90 were grouped for Buffalo, Hall, and Merrick counties which are located within the Nebraska Mid-State area. The normalized price elasticity of applied nitrogen fertilizer demand is estimated to be -0.34. Estimated inverse nitrogen fertilizer demand functions associated with alternative irrigation technologies are presented in Table 1.

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[1]The Erosion Productivity Impact Calculator (EPIC) simulation model has been used recently to estimate the rate of nitrate leaching as well as the fertilization efficiency coefficient (Chowdhury and Lacewell; Larson, Helfand, and House; Magleby, Selley, and Zara; Wu, Mapp, and Bernardo). These authors conducted EPIC simulation runs at different fertilizer application levels for each combination of crop, soil type, and irrigation runoff and percolation as well as the amounts of nitrogen fertilizer lost through runoff and leaching. Estimates of the amounts of nitrogen fertilizer lost through runoff and leaching are then regressed with the amounts of irrigation water and nitrogen fertilizer applied, which are used to estimate the rates of nitrate leaching and runoff.

The EPIC estimates for the amounts of irrigation water and fertilizer lost through runoff and leaching are somewhat variable. For instance, the EPIC simulation results reveal that more than 77 percent of irrigation water applied with a conventional furrow irrigation system would be lost through percolation on a Mid-Nebraska 15 county area with Crete silt loam soil (Magleby, Selley, and Zara). Furthermore, EPIC results show that a large portion of irrigation water applied would be lost through runoff when using a conventional furrow irrigation system on silt loam soil. Therefore, the reliability of the EPIC estimates for the fertilization efficiency rate associated with the unreasonable rates of irrigation efficiency would be questionable.

The time paths of the stock of nitrates in groundwater and the present value of net economic benefits resulting from nitrogen fertilizer use under two different scenarios are estimated and presented in Table 2. Estimated economic benefits under the nutrient management practices do not include costs associated with soil testing. The gains in the present value of net economic benefits as a result of adopting the nutrient management practices ranges from $186.60 per acre with a center-pivot irrigation system to $235.94 per acre with a conventional furrow irrigation system. At a 5 percent discount rate, these gains are equivalent to $9.33 per acre per year with a center-pivot irrigation system, $10.05 per acre per year with a surge-flow irrigation system, and $11.78 per acre per year with a conventional furrow irrigation system. These results indicate that farmers would be economically better off by adopting the nutrient management practices as long as the costs associated with soil testing are less than $9.33 per acre per year with a center-pivot irrigation system, $10.05 per acre per year with a surge-flow irrigation system, and $11.78 per acre per year with a conventional furrow irrigation system.

Results in Table 2 also indicate that groundwater quality under a conventional furrow irrigation system would deteriorate whether farmers adopt nutrient management practices or not. However, deterioration of groundwater quality under a conventional furrow irrigation system would be accelerated without nutrient management practices. Under a surge-flow irrigation system, groundwater quality would improve slightly with adoption of nutrient management practices, but it would deteriorate without adoption of nutrient management practices. Finally, groundwater quality would improve under a center-pivot irrigation system whether farmers adopt nutrient management practices or not. However, adoption of nutrient management practices under a center-pivot irrigation system would result in the improvement of groundwater quality from 18.7 ppm to 10.87 ppm.

In summary, adoption of nutrient management practices would result in increased net economic benefits to farmers and reduction of the nitrate stock in groundwater.

Table 1. Economic and hydrologic parameters pertaining to Merrick County, Nebraska.

Symbol	Description	Parameter value
α_o	Per acre inverse nitrogen fertilizer demand intercept.	0.67
β_c	The slope of consumptive N-fertilizer demand	0.00499
β_1	The slope of N-fertilizer demand with a furrow irrig. system	0.00324
β_2	The slope of N-fertilizer demand with a surge-flow irrig. system	0.00374
β_3	The slope of N-fertilizer demand with a center-pivot irrig. system	0.00424
ω	Saturated thickness (feet).	150
m	Specific yield[1].	0.25
N_o	The stock of nitrates in the underlying aquifer at the base year (lbs/ac.)	636.0
S_o	Residual nitrates in soil (lbs/a)[2].	49
P_Y	Unit price of corn ($/bushel).	2.30
n_i	The observed amounts of nitrogen fertilizer use (lbs/acre).	142.5
C_n	Unit cost of nitrogen fertilizer ($/nutrient lb).	0.17
σ_i	Fertilization efficiency.	
	i=1 for a conventional furrow irrigation system	0.65
	i=2 for a surge-flow irrigation system	0.75
	i=3 for a center pivot irrigation system	0.85
τ_i	The rate of leaching.	
	i=1 for a conventional furrow irrigation system	0.23
	i=2 for a surge flow irrigation system	0.15
	i=3 for a center pivot irrigation system	0.09
ρ_i or w_i	The rate of artificial discharge (ρ_i) or the ratio of the irrigation water applied per acre to the amount of groundwater available per acre from the underlying aquifer (w_i).	
	i=1 for a conventional furrow irrigation system	0.0375
	i=2 for a surge flow irrigation system	0.0325
	i=3 for a center pivot irrigation system	0.0287

1. Specific yield is defined as the unitless ratio of the volume of water a saturated rock or soil will yield under the influence of gravity to its own volume (Cleary, Miller and Pinder).
2. The residual nitrates in soil tested at 5 locations in Merrick County and reported by the 1993 Central Platte Natural Resources District are as follows: 3-year average of 26 lbs/a. at the Location 1 (T14,R7W), 8-year average of 35 lbs/a. at the Location (T14N, R7W); 2-year average of 85 lbs/a. at the Location 3 (T13N, R6W); 7-year average of 59 lbs/a. at the location 4 (T13N, R7W); and 5-year average of 44 lbs/a. at the location 5 (T13N, R8W). Weighted average residual is estimated to be 49 lbs/a.

Table 2. Trajectories for the stock of nitrates in groundwater ($N_i(t)$) and net economic benefits resulting from nitrogen fertilizer use with and without adopting nutrient management practices (NMP).

Irrigation technology	NMP	$N_i(t) = u_i + v_i exp[-w_i]t$			PV	ppm
		u_i	v_i	w_i		
Conventional furrow	yes	946.5	-310.5	.0375	582.46	27.83
	no	1,619.5	983.5	.0366	346.52	47.62
Surge-flow	yes	617.0	19.0	.0325	623.67	18.14
	no	992.0	356.0	.0276	422.91	29.17
Center-pivot	yes	369.8	266.2	.0287	660.10	10.87
	no	575.2	60.8	.0261	473.50	16.91

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