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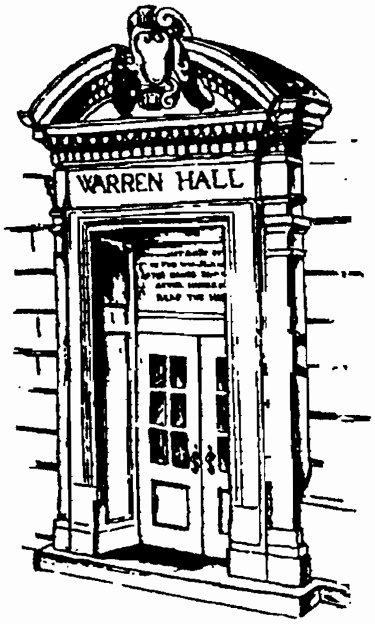

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BIOECONOMICS OF REGULATING NITRATES IN GROUNDWATER: TAXES, QUANTITY RESTRICTIONS, AND POLLUTION PERMITS

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BIOECONOMICS OF REGULATING NITRATES IN GROUNDWATER: TAXES, QUANTITY RESTRICTIONS, AND POLLUTION PERMITS

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Abstract

Soil specific, chance constrained, dynamic models of agricultural production and nitrate leaching are developed to assess the impacts of nitrogen fertilizer taxes, quantity restrictions on fertilizer or leachate, and leachate permits. A programming model uses the solutions of these bioeconomic models to determine regional impacts of the regulations.

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In recent years, concerns over groundwater quality have elevated due to increasing public awareness of contaminants in groundwater and the associated health hazards. Nitrates are the most widespread, many due to the leaching of nitrogen fertilizer used in agriculture (Kellog *et al.*, Nielson and Lee). In the 1990 *National Water Quality Inventory*, 37 states reported nitrates as their most common groundwater contaminant. Since over 50 percent of our nation's drinking water comes from groundwater sources (U.S.G.S.), the concern over nitrates has spurred numerous studies recently that examine the economic impact of regulatory policies designed to reduce nitrates in groundwater. Most have used soil-specific farm models to determine optimal fertilizer levels and crop rotations when taxes or quantity restrictions are placed on nitrogen fertilizer or leachate (e.g., Huang and Lantin, Taylor *et al.*, Painter).

To assess the effects of regulatory policies, any model of a farmer's use of nitrogen fertilizer and its relationship to nitrate leaching must: (i) consider year-to-year carryover effects on crop production and leaching and (ii) account for uncertainty due to weather and other factors that affect crop production and the amount of nitrogen leached. Theoretical work by Kim *et al.* and Kim and Hostetler shows that excluding time results in sub-optimal nitrogen fertilizer use. Johnson *et al.* include time only within the current growing season. Lambert concludes that excluding risk results in misleading costs and benefits of regulatory policies.

This paper contributes to the policy debate surrounding nitrate contamination of groundwater by solving an empirical, dynamic farm model that maximizes the present value of expected net revenue from agricultural production. The model embodies several features essential for evaluating policy alternatives. It is soil specific, includes management responses to environmental policy changes, accounts for year-to-year nitrogen carryover, and reflects uncertainty in both crop production and the dissemination of the pollutant. Models for several soils are used to compare typical policy options, taxes or quantity restrictions on nitrogen fertilizer or leachate, with leaching permits for a region in New York. Although pollution permits have been used mainly to regulate SO_2 emissions, they can potentially be used in regulating groundwater contaminants. Because this policy option is a relatively new alternative, a major focus of this research is on determining the economic stakes involved in a scheme of leachate permits, which involves finding farmers' demands for such permits.

Chance Constrained Bioeconomic Model

The model presented here is for corn and alfalfa (a common crop rotation in New York) with restrictions on nitrogen leaching, but it is adaptable for other crops grown in rotation or other leachable contaminants. Assume that a farmer maximizes the present value of expected net return from corn silage and alfalfa production.[1] Corn yield is a function of precipitation and nitrogen available in the crop root zone, which includes nitrogen inherent in the soil as well as nitrogen from manure and inorganic fertilizer. Alfalfa yield is a function only of precipitation, since this legume uses no nitrogen fertilizer. Alfalfa is grown in a 3-year rotation; after 3 years, the land must either be planted to corn or replanted to alfalfa. In addition to fertilizer application rates, the model includes variables for the fraction of land in first, second, and third year alfalfa, as well as corn following alfalfa and corn following corn. Precipitation is random, and crop yields and nitrate leachate are assumed stochastic. Mathematically the problem is:

$$\max \sum_{t=1}^{T} \rho^t \int_a^b [[p_{C,t} C(x_{1,t}, z_t) - r_{f,t} x_{1,t}^{fa} - r_{m,t} x_{1,t}^{ma}]\delta_{1,t} + [p_{C,t} C(x_{2,t}, z_t) - r_{f,t} x_{2,t}^{fa} - r_{m,t} x_{2,t}^{ma}]\delta_{2,t}$$

$$+ [p_{a1,t} a_1(z_t)]\delta_{3,t} + [p_{a2,t} a_2(z_t)](\delta_{4,t} + \delta_{5,t})] f_{Z_t}(z_t) dz_t$$

subject to

$$(1) \quad x_{1,t} = x_{1,t}^{fa} + x_{1,t}^{ma} + N_m + N_f$$

$$(2) \quad x_{2,t} = x_{2,t}^{fa} + x_{2,t}^{ma} + N_m$$

$$+ \gamma_1 [(\delta_{1,t-1}/(\delta_{1,t-1} + \delta_{2,t-1}))((1 - \gamma_2) x_{1,t-1} - \gamma_3 x_{1,t-1}^{fa} - 2\gamma_3 x_{1,t-1}^{ma} - L_{1,t-1})$$

$$+ (\delta_{2,t-1}/(\delta_{1,t-1} + \delta_{2,t-1}))((1 - \gamma_2) x_{2,t-1} - \gamma_3 x_{2,t-1}^{fa} - 2\gamma_3 x_{2,t-1}^{ma} - L_{2,t-1})]$$

$$(3) \quad L_{i,t} = g(z_t)[(1 - \gamma_2) x_{i,t} - \gamma_3 x_{i,t}^{fa} - 2\gamma_3 x_{i,t}^{ma}] \text{ for } i = 1,2$$

$$(4) \quad \mathrm{Prob}[\delta_{1,t} L_{1,t} + \delta_{2,t} L_{2,t} \geq L_U] \leq \alpha$$

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[1] Without loss of generality, this model reflects production on one acre of a specific soil. Differences in production patterns among soils are identified through replications of the model.

$$(5)\ \delta_{1,t} \le \delta_{5,t-1}, \quad (6)\ \delta_{2,t} \le \delta_{1,t-1} + \delta_{2,t-1}, \quad (7)\ \delta_{4,t} \le \delta_{3,t}$$

$$(8)\ \delta_{5,t} \le \delta_{4,t-1}, \quad (9)\ \sum_{i=1}^{5} \delta_{i,t} \le 1 \quad (10)\ x_{i,t}^{ma} \le \bar{x}^{m} \text{ for } i = 1,2$$

$$(11)\ x_{1,t}^{fa},\ x_{1,t}^{ma},\ x_{2,t}^{fa},\ x_{2,t}^{ma},\ \delta_{1,t},\ \delta_{2,t},\ \delta_{3,t},\ \delta_{4,t},\ \delta_{5,t} \ge 0$$

where t is time (year); ρ is the discount factor (1/(1+discount rate)); p_C is the net price of corn silage, excluding the cost of fertilizer ($/ton); C(·) is the production function for corn (tons/acre); $x_{1,t}$ is nitrogen available for corn in t following alfalfa in t-1 (lb./acre); z is precipitation (in.); r_m is the cost of nitrogen from manure ($/lb.); r_f is the price of inorganic nitrogen fertilizer ($/lb.); $x_{1,t}^{fa}$ is inorganic fertilizer applied on corn in t following alfalfa in t-1 (lb./acre); $x_{1,t}^{ma}$ is nitrogen from manure applied on corn in t following alfalfa in t-1 (lb./acre); $\delta_{1,t}$ is the fraction of land in corn in t following alfalfa in t-1; $x_{2,t}$ is nitrogen available for corn in t following corn in t-1 (lb./acre); $x_{2,t}^{fa}$ is inorganic fertilizer applied on corn in t following corn in t-1 (lb./acre); $x_{2,t}^{fa}$ is nitrogen from manure applied on corn in t following corn in t-1 (lb./acre); $\delta_{2,t}$ is the fraction of land in corn in t following corn in t-1; p_A is the net price of alfalfa ($/ton); $A_1(\cdot)$ is the production function for first-year alfalfa (tons/acre); $\delta_{3,t}$ is the fraction of land in first-year alfalfa; $A_2(\cdot)$ is the production function for second and third year alfalfa (tons/acre); $\delta_{4,t}$ is the fraction of land in second year alfalfa; $\delta_{5,t}$ is the fraction of land in third year alfalfa; N_f is nitrogen fixed by alfalfa (lb./acre); L_t^1 is nitrogen leached below the crop root zone in t on land in corn in t following alfalfa in t-1 (lb./acre); L_t^2 is nitrogen leached in t on land in corn in t following corn in t-1 (lb./acre); N_m is the nitrogen from precipitation and mineralized from soil organic matter (lb./acre); and L_U is the upper bound on nitrogen leachate (lb./acre).

Equation (1) is the transition equation for nitrogen available for corn in t following alfalfa in t-1. Nitrogen available in t is nitrogen applied in t plus the residual nitrogen fixed by previous alfalfa and accumulated through precipitation or mineralized by soil organic matter. Equation (2) is the transition equation for nitrogen available for corn in t following corn in t-1. Unlike corn following alfalfa, no nitrogen is fixed by the previous year's crop, but some nitrogen available in the previous year may be carried over. Nitrogen available for corn in t following corn in t-1 is nitrogen fertilizer applied, plus nitrogen accumulated in precipitation or mineralized, plus some fraction of nitrogen that is not uptaken by the plant, $(1-\gamma_2)x_{i,t-1}$, nor denitrified, $\gamma_3(x_{i,t-1}^{f\,a}+2x_{i,t-1}^{m\,a})$,[2] nor leached, L_{t-1}^{i}. Finally, nitrogen carryover is a weighted average of carryover from corn in t-1 following alfalfa in t-2 and corn in t-1 following corn in t-2.

Equations (3) and (4) trace and restrict nitrogen leaching below the crop root zone. Nitrogen leaching is a fraction of the nitrogen available after plant uptake and denitrification. The fraction leached, $g(z)$ where $0 \leq g(z) \leq 1$, depends on precipitation and is soil specific. Using this relationship and the density for rainfall, a chance constraint on nitrogen leachate, (4), consistent with Lichtenberg and Zilberman's policy recommendation, guards against worst-case scenarios by allowing leaching to exceed a harmful upper bound with only a small probability. Total leachate is a weighted average of that for land in corn since alfalfa uptakes most of the nitrogen it fixes (Meisinger and Randall), and leaching is assumed not a problem while land is in alfalfa. Equations (5)-(9) ensure consistent crop rotations and crop proportions. Equation (10) is a limit on the amount of manure a farmer can apply, since farmers do not have an infinite supply of manure and generally only apply 10 to 15 tons of manure per acre (Schmit). Equation (11) is the non-negativity of the variables.

Empirical Application to New York Soils

To provide a preliminary examination of the effects of policy options for regulating nitrate leachate in New York, the bioeconomic models are constructed and solved for seven soils in Genesee and Wyoming Counties in New York. The seven base soils are given in Table 1 and are chosen because they are thought to reflect the major differences in leaching and productivity among soils in the region. In order to analyze policies at the regional level, other soils producing crops in Genesee and Wyoming Counties are matched to one of the seven base soils according to leaching potential and productivity. Characteristics of the soils in the region are obtained from SCS Soils-5 data; cropland acreages are from 1982 NRI data.

Regional soils are matched to the seven base soils according to hydrologic group (which reflect differential capacities of soils to permit infiltration), the organic matter content, and the drainage classification of the soil (Table 2). The primary differences in leaching and productivity are assumed to be accounted for by hydrologic group. Possible hydrologic groups are A, B, C, and D, with group A soils typically being lighter, more productive soils and group D soils being the heaviest and least productive. Corn and alfalfa are only grown on hydrologic group A, B, and C soils. Two of the seven base soils are from hydrologic group A; two are

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[2] Nitrogen from organic sources, such as manure, denitrifies at twice the rate of inorganic nitrogen fertilizer (Meisinger and Randall).

Table 1. General Characteristics of the Base Soils

Base Soil	Associated Soil Name	USDA Texture Class	Hydro-logic Group	Average Organic Matter (%)	Average Slope (%)	Drainage Classification
N-A	Chenango	Gravelly Loam	A	4.0	3	Well Drained
N-B	Tunkhannock	Gravelly Silt Loam	A	3.0	5	Well Drained
N-C	Lima	Silt Loam	B	4.0	3	Moderately Well Drained
N-D	Unadilla	Silt Loam	B	4.5	9	Well Drained
N-E	Collamer	Silt Loam	C	3.5	4	Moderately Well Drained
N-F	Minoa	Very Fine Sandy Loam	C	4.5	0	Somewhat Poorly Drained
N-G	Bath	Channery Silt Loam	C	4.5	5	Well Drained

from hydrologic group B; and three are from hydrologic group C. After sorting soils by hydrologic group, soils are grouped according to the average organic matter content. Finally, further distinction is needed to match regional soils to N-F and N-G soils. This distinction is made by differences in drainage classification. The resulting regional percentages and acreages of the soils are given in Table 3.

Table 2. Classification of Soils in Genesee and Wyoming Counties into the Seven Base Soils

Base Soil	Classification		
	Hydrologic Group	Organic Matter (%)	Drainage Class
N-A	A	≥ 4	
N-B	A	< 4	
N-C	B	< 4	
N-D	B	≥ 4	
N-E	C	< 4	
N-F	C	≥ 4	not Well Drained or Moderately Well Drained
N-G	C	≥ 4	Well Drained or Moderately Well Drained

Table 3. Soil Percentages in Genesee and Wyoming Counties in New York

Soil	Percent of the Cropland in the Region[a]	Acres[b]
N-A	3.9	5,106
N-B	5.8	7,594
N-C	7.4	9,689
N-D	31.9	41,768
N-E	4.7	6,154
N-F	28.0	36,661
N-G	18.3	23,961

[a] These percentages are calculated using cropland acreages from the 1982 National Resource Inventory data.

[b] Acreages are determined using the percentages in this table and the total corn and alfalfa acres harvested in New York of 130,933 (*1987 Census of Agriculture*). Individual acreages may not sum to this number due to rounding.

Estimating Parameters. Before solving the model, a number of functional relationships are estimated. These include: the corn and alfalfa response relations, probability distributions for precipitation affecting yield and leachate, the leachate function from equation (3).

Corn production functions are assumed to be quadratic (Hexem and Heady; Heady and Dillon). Stuart Klausner in the Department of Soil, Crop and Atmospheric Sciences at Cornell University provided corn response data to nitrogen fertilizer application for the seven base soils in New York (1985-1991). Precipitation data are April through September precipitation from nearby weather stations. In addition, estimates of the amount of nitrogen in the crop root zone other than that from fertilizer are obtained using NLEAP, a simulation package that traces nitrogen movement (Shaffer *et al.*). To account for productivity differences between the seven base soils, separate production functions are estimated for soils with identical hydrologic groups (Table 4).

Table 4. Corn Silage Response to Nitrogen (X) and April-September Precipitation (Z)

Hydrologic Group A ($R^2 = 0.50$)						
$C =$	-11.1702	$+ 0.1945\ X$	$- 0.00016\ X^2$		$+ 0.0301\ Z^2$	$- 0.0033\ XZ$
t:		(8.01)	(-5.50)		(6.90)	(-4.90)
Hydrologic Group B ($R^2 = 0.76$)						
$C =$	71.2438	$+ 0.2218\ X$	$- 0.00019\ X^2$	$- 7.8497\ Z$	$+ 0.1988\ Z^2$	$- 0.0036\ XZ$
t:		(7.32)	(-5.32)	(-5.25)	(6.30)	(-3.60)
Hydrologic Group C ($R^2 = 0.61$)						
$C =$	-62.2010	$+ 0.1166\ X$	$- 0.00018\ X^2$	$+ 7.2716\ Z$	$- 0.2165\ Z^2$	$+ 0.0014\ XZ$
t:		(3.76)	(-4.53)	(4.27)	(-4.68)	(1.10)

Estimating the alfalfa responses to precipitation requires data by soil on both first-year and established alfalfa yields. However, soil-specific data were unavailable. Also, data on first-year alfalfa yields and alfalfa yields from established stands were unavailable. For these reasons, no response relationships are estimated. Instead, expected yields are assumed to be 3 and 4 tons/acre for first-year and established alfalfa, respectively. These yields fall into the yield range of 3 to 6 tons/acre in New York given by the *Cornell Field Crops Handbook.*

To begin estimating the equation for nitrogen leaching, $g(z)$ is assumed to take on the following functional form: $g(z) = 1 - \exp(-\lambda z)$. This function is bounded between zero and one and makes (3) similar to the leaching equation in EPIC, a nitrogen leachate simulator (Williams and Kissel). Data used to estimate (3) are generated from NLEAP (Shaffer *et al.*). Twelve-month precipitation is used to predict leachate. Non-linear least squares estimates of λ are given in Table 5. *Ceteris paribus*, larger estimates of λ are indicative of greater leaching. As expected, the estimates for the hydrologic group A and B soils are greater than those for the group C soils.

Table 5. Estimated Parameters for the Leaching Equations

Soil	λ	t-ratio	R^2 [a]
N-A	0.029440	83.81	0.93
N-B	0.010155	90.72	0.91
N-C	0.006871	44.13	0.68
N-D	0.023017	44.99	0.77
N-E	0.005567	31.73	0.60
N-F	0.009497	30.73	0.59
N-G	0.006510	31.69	0.63

[a] The R^2 values indicate the goodness of fit. However, they cannot be interpreted as true R^2 values either because λ is estimated using NLS or because λ is estimated using OLS without an intercept (Judge, *et al.*, 1985).

In this regional analysis, precipitation is assumed to be the same across soils in the region. Similar to Dai *et al.*, precipitation is assumed to follow a beta density:

$$(12) \quad f(z;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot \frac{z^{\alpha-1}(z_u - z)^{\beta-1}}{z_u^{\alpha+\beta-1}} \quad \text{for } 0 \le z \le z_u; \quad \alpha,\beta > 0; \quad \Gamma(\psi) = \int_0^\infty e^{-t} t^{\psi-1},$$

Although the two-parameter beta density is flexible, the likelihood function maximized to estimate α and β must be numerically approximated because the gamma functions contain the two parameters. Mathematica is used to perform the maximum likelihood (ML) estimation because it can call Gamma functions directly (Wolfram). The ML estimates are given in Table 6. Kolmogorov-Smirnov tests for goodness of fit (Spanos) are used rather than Chi-square because of potential bias introduced when subjectively selecting intervals for the Chi-square. All tests are significant at the one percent level. The 12-month distribution is skewed slightly to the left, and the 6-month distribution is skewed slightly to the right. However, neither is skewed dramatically, as indicated by the skewness coefficients near zero.

Table 6. Maximum Likelihood Estimates and Distributional Characteristics of the Precipitation Variables

Precipitation Variable	α_{ML}	β_{ML}	Mean[a]	Standard Deviation[b]	Skewness[c]	$D\sqrt{n}$[d]
12-month	17.66	13.42	34.1	5.2	-0.09	0.71
6-month	9.00	9.38	19.6	4.5	0.02	0.80

[a] The mean, μ, is given by $\dfrac{\alpha z_u}{\alpha + \beta}$.

[b] The standard deviation, σ, is given by $\left[\dfrac{\alpha\beta z_u^2}{(\alpha+\beta)^2(\alpha+\beta+1)}\right]^{1/2}$.

[c] The skewness coefficient, τ, is given by $\dfrac{2\alpha\beta(\beta-\alpha)z_u^3}{\sigma^3(\alpha+\beta)^3(\alpha+\beta+1)(\alpha+\beta+2)}$.

[d] $D\sqrt{n}$ is the test statistic for the Kolmogorov-Smirnov test for goodness of fit.

Since g(z) is invertible and separable in (3), the left-hand side of (4) becomes:

$$(13)\quad \text{Prob}\left[z \geq -\frac{1}{\lambda}\ln\left[1 - \frac{L_U}{\delta_1 NAL_1 + \delta_2 NAL_2}\right]\right].$$

where $NAL_{i,t} = (1-\gamma_2)x_{i,t} - \gamma_3(x_{i,t}^{f\ a} + 2x_{i,t}^{m\ a})$ is nitrogen available for leaching on corn following alfalfa, i=1, or corn following corn, i=2. Using the density, z_α is found such that $\text{Prob}[z \geq z_\alpha] = \alpha$. The chance constraint becomes:

$$(14)\quad z_\alpha \geq -\frac{1}{\lambda}\ln\left[1 - \frac{L_U}{\delta_1 NAL_1 + \delta_2 NAL_2}\right]$$

which reduces to:

$$(15)\quad \left(1 - e^{-\lambda z_\alpha}\right)\left[\delta_1 NAL_1 + \delta_2 NAL_2\right] \leq L_U.$$

Most prices are 1991 prices from *New York Agricultural Statistics*. Variable costs are from production budgets (Greaser). The cost of nitrogen from manure is calculated using a Pro-Dairy worksheet. Manure is assumed to contain 3.5 lbs. of nitrogen per ton, and application is restricted to no more than 15 tons/acre. Alfalfa is assumed to fix 175 pounds of nitrogen, N_f (*Cornell Recommends*). Other parameters (plant uptake of nitrogen, etc.) are from Follett *et al.*

Empirical Results. Following Standiford and Howitt, who solved empirical models of similar dimensions, the dynamic optimization models are solved for a 20-year time horizon using GAMS/MINOS. Base models are solved initially without the chance constraint on nitrogen leachate. To depict current crop rotations in the region, a minimum crop rotation of 40 percent alfalfa is imposed. Table 7 gives values towards which the base models converge.

Table 7. Unrestricted Per Acre Annual Production, Leachate, and Farm Returns by Soil

Soil	20-Yr. Discounted Expected Net Return	$E(C_1)$	$E(C_2)$	x_1^a	x_2^a	Fraction of Acre in Corn	Fraction of Acre in Alfalfa	Annual Expected Leachate Per Acre
N-A	$1672	21.2	20.5	53	182	0.6	0.4	38.9
N-B	1682	21.1	20.6	53	178	0.6	0.4	18.2
N-C	1765	21.7	21.2	35	154	0.6	0.4	13.1
N-D	1775	21.7	21.1	19	148	0.6	0.4	35.8
N-E	1446	16.7	16.2	19	133	0.6	0.4	11.2
N-F	1474	16.7	16.2	0	119	0.6	0.4	17.1
N-G	1400	16.8	16.2	47	162	0.6	0.4	13.0

Note: x_1^a and x_2^a are total nitrogen fertilizer applied per acre, which includes nitrogen from both manure and inorganic fertilizer.

In the base models, the net present value of expected returns are highest for the hydrologic group B soils, N-C and N-D (Table 7). Because continuous corn is relatively more profitable than alfalfa, alfalfa comes into rotation only at the minimum bound of 40 percent alfalfa land. The most fertilizer is applied to the more leachable group A soils, N-A and N-B; whereas typically the least is applied on the hydrologic group C soils, N-E, N-F, and N-G. Expected annual leachate is the greatest on the group A and B soils, ranging from about 15 to 40 lbs./acre. Expected leachate on the group C soils is typically around 15 lbs./acre.

Chance-constrained models are then solved for two probability levels, $\alpha = 0.05$ and $\alpha = 0.25$. Upper bounds are varied in 2.5 lb. increments over the range from no leaching to the unrestricted leaching levels identified in the base models. When chance constraints on nitrate leachate are imposed, the bioeconomic models must respond by either decreasing the nitrogen fertilizer application rate or increasing the land producing alfalfa in the crop rotation. Typically, the models respond first by decreasing nitrogen fertilizer application when chance-constraints are less restrictive. Then, as the chance-constraints become more restrictive, the fraction of the acre producing alfalfa is increased as well.

A System of Pollution Permits

The chance-constrained solutions to the bioeconomic models are used to develop a system of pollution (leachate) permits. Assuming that each leachate permit allows one pound of expected leachate per year, parametric demand schedules for leachate permits can be determined for each soil. To illustrate, suppose the objective function values and expected leachate levels corresponding to the chance-constraint for a soil are as given in Table 8. Given this information, if a farmer wants to increase expected leachate from no leachate to 4 lbs. (or, equivalently, initially buy 4 permits) on an acre of this soil, it is worth an additional $250, or $62.50 per pound (or per permit). Likewise, an additional 4 pounds of leachate (or an additional 4 permits) to go from 4 to 8 lbs. of leachate would be worth $37.50 per pound (or per permit). By following this procedure for the remaining leachate levels, a parametric demand schedule is obtained. The demand is illustrated in Figure 1. In the empirical analysis, the number of increments is much larger because of the large number of chance-constrained models solved, giving a more precise demand schedule.

Table 8. An Example for Calculating the Per Acre Demand for Pollution Permits on a Specific Soil

Objective Function Value (1)	Expected Leachate (2)	Change in Objective Function (3)	Change in Leachate (4)	Permit Price (3)/(4)
$1300	0			
1550	4	$250	4	$62.50
1700	8	150	4	37.50
1800	12	100	4	25.00
1850	16	50	4	12.50

To illustrate how this information may be used to assess the regional impacts of a leaching permit scheme, a programming model was formulated that determines the soil-specific quantity of permits demanded at a given price using the relative weights of soils within the region. The model determines the quantity of permits demanded on individual soils at a given price by maximizing the economic surplus that an agency selling permits could obtain if it were a perfectly price discriminating monopolist. Restrictions in the model are the weighted quantity steps along the parametric demand schedules.

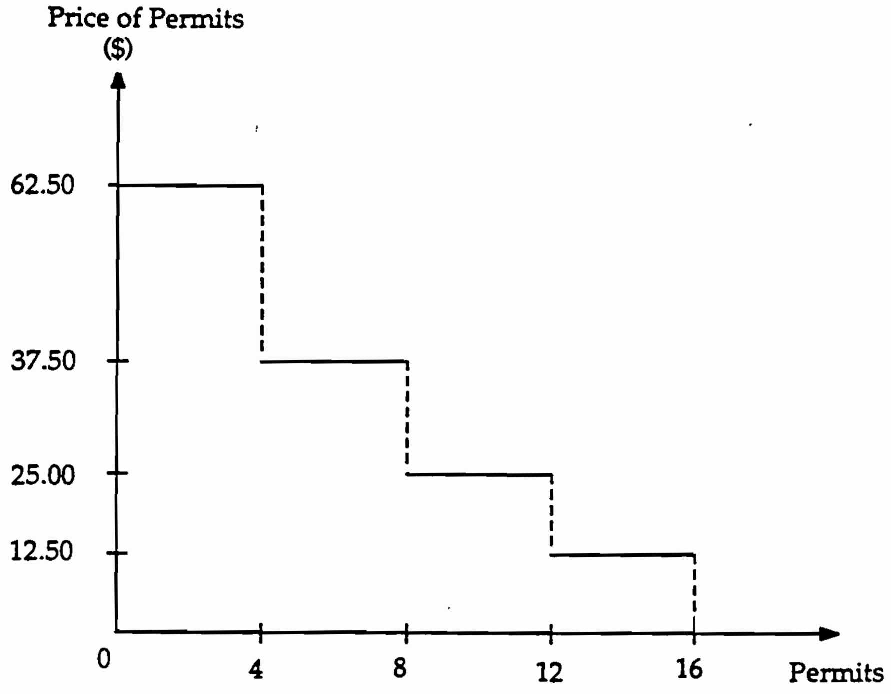

Figure 1. Parametric demand for Leachate Permits Per Acre

Results of the programming model for the region of Genesee and Wyoming County in New York are given for two permit prices in Table 9. The prices, $8.34 and $15.55, are those that would be required to reduce regional expected leachate by 10 and 25 percent, respectively.[3] If permits are sold for $8.34, then the most permits demanded per acre are on the hydrologic group A and B soils, especially N-A and N-D soils. This is because these soils are the most productive but also have a relatively high leaching potential. The least are demanded on the hydrologic group C soils. If permits are sold for $15.55, then the quantity of permits demanded per acre decreases. Most dramatically, the number of permits demanded on N-A and N-G soil decrease nearly 50 percent. Although N-A soil is a relatively productive soil, its high leaching potential makes purchasing permits less profitable. For N-G soil, the low productivity is the dominant factor responsible for the decrease in the quantity of permits demanded. Regional economic surplus from leaching accruing to the farmers (which is the objective function of the programming model that determines the quantities of permits demanded) decreases from $55.4 million to $49.8 million (or from $423 to $380/composite acre) when the permit price increases from $8.43 to $15.55/permit.

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[3] Regional expected leachate for the unrestricted base cases given in Table 7 (the equivalent of free leaching permits) is 2.97 million lbs. or 22.7 lbs. per acre of a composite soil.

Table 9. Quantities of Permits Demanded Per Acre on Specific Soils when Permits are Sold at a Fixed Price

Permit Price:	$8.34	$15.55
Soil	Quantity of Permits Demanded	Quantity of Permits Demanded
N-A	32.8	17.6
N-B	16.6	16.0
N-C	12.3	12.3
N-D	32.4	28.1
N-E	10.2	10.2
N-F	16.0	12.4
N-G	10.3	6.8

Policy Implications

The previous section demonstrates how solutions to the dynamic models developed in this paper can be used to articulate demands for leachate permits. To understand the policy significance of such a scheme, it is important to compare the cost and effectiveness of the permit system with policies directly regulating the quantity of leachate or indirectly regulating it through a tax or quantity restriction on nitrogen fertilizer. These alternative policies can be examined directly in the bioeconomic models if the chance-constraint on nitrate leachate is removed.

Suppose, for example, that regional leachate is to be reduced 10 percent. Average annual leaching on an acre comprised of composite soils decreases from 22.7 lbs./acre to 20.4 lbs./acre. If farmers voluntarily decrease leachate to this level, farm revenues decrease by $11/acre, which also represents the amount farmers lose if tradable permits are freely allocated by a regulatory agency.[4] If farmers are required to purchase permits at a fixed price, not only do they lose the $11, but they also lose the amount they must pay for leachate permits, which is ($8.34/permit)(20.4 permits) = $171/acre. A 38 percent tax would have to be imposed on nitrogen fertilizer to achieve the same 10 percent reduction in regional leachate, resulting in a farm cost of $42/acre. Uniformly restricting nitrogen fertilizer application rates would result in a cost of $18/acre, and directly reducing leachate by 10 percent of historic leaching on all soils would result in a farm cost of $13/acre. These farm costs for the policies of freely distributed tradable permits, permits sold at a fixed price, taxing fertilizer, restricting

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[4] Farm revenues and costs reported here are the present value of expected revenues and costs over the 20-year planning horizon.

fertilizer, and restricting leachate represent 0.7, 11.5, 2.6, 1.1, and 0.8 percent of the present value of current 20-year expected net farm returns, respectively. They also represent 1.6, 25.2, 5.8, 2.4, and 1.8 percent of current land values.[5] (*New York Agricultural Statistics*). The incidence of the costs of each differ. Both leachate permits sold at fixed prices and taxes on fertilizer generate public revenues. For instance, for the 10 percent reduction in regional leachate, public revenues generated per acre are $171 and $28 for these policies, respectively. No public revenues are generated from the other policies.

The research reported in this paper has been concerned primarily with comparing the economic stakes involved in schemes of pollution permits with those of quantity restrictions and taxes. While these stakes are quite different in magnitude when permits are sold at fixed price, an alternative permit scheme may be more feasible. For instance, a free initial allocation of permits could be made based on historic leaching levels. Since this scheme would dramatically decrease the farm costs associated with leachate permits, the desirability of alternative policies will hinge in large measure on issues surrounding administrative and enforcement costs. Thus, for any of these policies, additional effort must be devoted to identifying effective enforcement strategies, some of which may include randomly sampling soil nitrogen levels.

These administrative and enforcement costs may be quite large for the permit schemes, but even policies that are less costly administratively may not lead automatically to correct fertilizer application rates on particular soils. For example, although a policy such as the fertilizer tax might be relatively inexpensive to implement, it does not necessarily restrict leaching on highly vulnerable soils. In certain regions, this may be a more important issue than simply restricting total leachate, if soils are highly leachable above an aquifer that is a source of drinking water for many people in a region. Under these conditions, one may want to restrict leaching on soils that contribute most to nitrate levels in that aquifer and essentially use the permit system to "transfer" leachate to other soils in the region. This strategy is similar to the proposed trading of point and nonpoint source pollutants under the Coastal Zone Management Act for which Letson *et al.* have identified between 30 and 40 specific sites where such a trading scheme might be effective and be administratively feasible.

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[5] The current land value used is $727/acre. This is calculated using the average value per acre of land and buildings in New York of $1119 (*New York Agricultural Statistics*) and assuming that buildings account for 35 percent of this value.

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