Articles

Marginal Abatement Costs of Reducing Groundwater-N Pollution with Intensive and Extensive Farm Management Choices

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Cost-effectiveness is an important consideration in evaluating choices for meeting environmental quality objectives. Estimated crop yield response functions and the associated groundwater-nitrate pollution production functions were used to evaluate the optimal N fertilization and on-farm abatement costs for alternative cropping systems, with management choices at both the intensive and extensive margins. The cost-effective corn production system, which meets the Health Canada standard for nitrates with the highest returns ($278 ha^{-1}) and lowest on-farm abatement cost ($248 ha^{-1}), was a four-year corn-corn-soybean-wheat rotation under conventional tillage. At contaminant limits above the Health Canada standard, the cost-effective wheat cropping system shifted from a soybean-wheat rotation under no-tillage to a corn-soybean-wheat rotation under no-tillage.

Several recent studies document evidence of nitrate-N leachate loss to groundwater from agricultural sources in Ontario (Fleming 1992; Frank, Chapman, and Johnson 1991; Howard and Falck 1986; Lee-Han and Hatton 1991; Rudolph et al. 1992; Rudolph and Goss 1993). Nitrate pollution from agriculture is a key groundwater contaminant in rural areas in Ontario, where approximately 90% of the population depend on groundwater supply (Neufeld 1987). Groundwater-N pollution can have various adverse effects on human health and on environmental quality (Fraser and Chilvers 1981; Sullivan et al. 1991). Increasing public awareness of and demand for environmental amenities are changing attitudes about agriculture and the agricultural industry's implicit property rights (Batie 1988). One response to this change is a growing use of public policy options for mitigating agricultural pollution problems. First-best solutions to pollution control problems require knowing each firm's marginal abatement cost (MAC), because this firm-specific knowledge will permit a derivation of the most efficient level of pollution control. Given the practical difficulty of determining the marginal external cost (MEC) function, an alternative approach for determining the optimal pollution is to use an externally determined standard in setting the framework for resource allocation (Goody and O'Hara 1995). The drinking water standard, which in the case of nitrate-N is 10 mg N L^{-1}, replaces the "pollution optimum." Consequently, the resource allocation problem involves attaining this given groundwater quality objective through, for example, a reduction in N fertilization.

Evaluating the cost effectiveness of agricultural pollution control policies is usually based on the general rule that efficiency is improved by adjusting farm management practices and reallocating abatement costs to management choices with lower MACs (McSweeny and Shortle 1990). The use of best management practices for controlling nonpoint source pollution does not always provide cost-minimizing abatement strategies (Segerson 1988), in part because these practices do not allow for flexibility among alternative farm management choices. Reduction of groundwater-N leaching, for example, requires adjustments in farm management choices at the intensive margin (e.g., N fertilization rates) and/or at the extensive margin (e.g., crop choice and rotation).

Empirical studies on nonpoint source pollution control from agriculture often integrate biophysical simulation models with an economic farm optimization model (King et al. 1993; Taylor, Adams, and Miller 1992). Generally, the analysis involves a mathematical programming model that forces the

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management decisions to be selected from a discrete set of choices such as fertilization rate (high, medium, or low), tillage (conventional or conservation), or rotations (Randhir and Lee 1997; Weersink, Dutka, and Goss 1996). The acceptable contaminant limits, as predicted by the biophysical simulation model, are imposed as a constraint on the programming model. Enforcing the constraint reduces profits from the unregulated optimum level and thereby measures the abatement cost of the environmental protection. Studies that have used this approach to obtain on-farm abatement costs include Helfand and House (1995), Huang, Shank, and Hewitt (1996) and Johnson, Adams, and Perry (1991) for nitrates; Taylor, Adams, and Miller (1992) for phosphorus (and nitrates); and Boggess et al. (1979) for soil loss control. Helfand and House (1995) offer the only study that examines the MAC of two systems for growing a single crop with an intensive management choice (N fertilization and irrigation water levels). Previous work has not considered intensive and extensive management choices together in examining on-farm abatement costs of alternative farming systems. Neither have explicit MAC functions been developed.

The purpose of this study is to explicitly determine the on-farm MAC associated with reducing groundwater-N leaching loss under alternative farming systems. The study focuses on characterizing the MAC curve in order to evaluate the cost effectiveness of meeting specific environmental quality standards. The use of estimated crop yield response and the associated groundwater-N leaching functions permits evaluation of the optimal N fertilizer rates and on-farm abatement costs for alternative farming systems as continuous choice variables. Thus, the approach is most useful when one has to consider the cost-minimizing abatement strategies associated with groundwater-N pollution reduction under alternative farming systems.

Theoretical Model: Deriving Abatement Costs

A representative farmer is faced with farming system choices consistent with Antle and Just (1991), which include decisions at the extensive margin regarding crop choice, crop rotation, and tillage treatment, and at the intensive margin regarding nitrogen fertilization rate (N). Abatement costs for three different scenarios categorized on the basis of the management choices available to producers are derived. Initially, only extensive discrete options exist: this is the typical approach used in most empirical studies. Then, the MAC function is derived and illustrated for an intensive management choice. Comparative statics are used to determine the shifts in the MAC. Finally, abatement costs are developed in the case where both extensive and intensive choices exist.

Extensive Management Choices

The on-farm abatement cost for meeting a given environmental quality standard (L^R) with extensive management choices is the difference between maximum unregulated profits (π^*) and maximum profits under the regulation requiring L^R not to be exceeded, (π^R). Regulated profits are a function of relative prices (w) and the environmental quality objective. π^R is found by solving the following constrained maximization problem:

$$\text{(1)} \quad \pi^R(w, L^R) = \underset{\{X_i\}}{Max} \sum_{i=1}^{n} \pi_i^E(w) X_i + \lambda\left[L^R - \sum L_i X_i\right] + \mu\left[\overline{X} - \sum X_i\right],$$

where n is the total number of crop rotation systems, $\pi_i^E(w)$ is the net returns per unit area for rotation system i in which intensive management choices are fixed, X_i is the area devoted to a discrete management choice i, λ is the marginal abatement cost, L_i is the contaminant amount generated per unit area planted to system i, L^R is the total acceptable level of N contamination, μ represents the marginal returns to an extra unit of land, and $\overline{X}$ is the total land resource base, normalized as ($\overline{X}$ = 1) in order to generate profit on per unit area basis. Without other constraints, and given the linearity of the objective function, the firm will devote all the available land to the farming system that generates the greatest net returns per unit area. The optimal system chosen may change if the environmental objective changes. Consequently, the MAC curve will be a stepwise function for this problem with a discrete choice set of extensive management choices. Examples of studies that have used this approach to estimate abatement costs include Randhir and Lee (1997) and Weersink, Dutka, and Goss (1996).

Intensive Management Choices

Given management choices at the intensive margin, the MAC curve will be a smooth twice continuously differentiable function generally if the production functions for both crop and pollution are smooth and continuous. The producer can still adjust to meet L^R through intensive management choices such as fertilization rate even if the extensive choices such as crop rotation are fixed. For example, assume the level of output per unit area for a given crop (Y) depends on the nitrogen fertilizer rate applied (N) as summarized by the crop production function, $Y = F(N)$, where $F(N)$ is twice continuously differentiable. The fertilizer input not only produces a crop but also generates groundwater-N pollution or leachate (L) given by $L = L(N)$.

Absence of a groundwater-N leaching constraint implies that the resource is "free" since no well-defined property rights to the assimilative capacity of the groundwater system exist. With no regulations on groundwater nitrates, the optimal level of N fertilizer applied to a given crop and the associated groundwater leachate level is determined by maximizing the following profit function, ($\pi(w)$):

$$\pi(w) = \underset{\{N\}}{Max}\, F(N) - wN - C, \tag{2}$$

where w is the normalized input-output price ratio ($\hat{w}/p$), p and $\hat{w}$ are the respective per unit crop and N fertilizer prices, and C represents normalized cost of production for the crop other than N fertilizer cost. The only costs to the farmer from the use of nitrogen fertilizer are its purchase costs and not any associated environmental costs. Solving explicitly for the level of N fertilizer generates the per unit area fertilizer demand function for the crop: $N^* = N^*(w)$. Substituting N^* into the appropriate functions results in the corresponding output supply ($F^*(w)$), profit ($\pi^*(w)$), and groundwater-N leaching ($L^*(w)$) functions. The optimal levels of these endogenous variables depend not only on prices but also on the underlying production technology that varies with the crop under consideration, crop rotation it is grown in, and tillage choice.

The solution to the unregulated profit maximization problem involving an intensive management choice is illustrated in figure 1. The profit function $\pi^*(w)$ shows maximum net returns for the level of N fertilization rate (panel A). Both profit functions are nonincreasing in $\hat{w}$ and nondecreasing in p. In the case of cropping system 1, profits ($\pi_1(w)$) are maximized at N_1^* (panel A), which generates a leachate level L_1^* (panel B). In comparison with system 1, system 2 is more profitable at fertilizer rates less than N^E but less profitable at rates above N^E. At rates above N^E, optimal profits (π_2^*), N fertilization rate (N_2^*), and leachate (L_2^*) for system 2 are all less than the corresponding values for system 1.

If there is a regulation to restrict the level of groundwater-N leached (L^R) and the farmer is restricted to a given farming system with the only management option being changing the fertilization rate, the first-best solution involves solving the following problem:

$$\pi^R(w, L^R) = \underset{\{N\}}{Max}\, F(N) - wN - C + \lambda[L^R - L(N)], \tag{3}$$

where λ is the normalized MAC of a unit reduction in groundwater-N leaching standard (L^R). The profit-maximizing nitrogen demand, which is found by evaluating the inverse N leachate function, is now a function of only the groundwater-N leachate standard and not relative prices: $N^R = L^{-1}(L^R)$. With only one choice variable, there is no substitution between inputs prompted by a price change. Thus, the level of nitrogen is determined by the pollution function. Solving the Kuhn-Tucker FOCs results in a marginal abatement cost function, $\lambda = \lambda(w, L^R)$.

The effect of the environmental regulation on the intensive management choice and farm profits can be illustrated through figure 1. The right side of figure 1 summarizes the effects of the leachate regulation on farm returns. For example, if the leachate standard is L_A^R, then the fertilizer rate will be N_{1A} (N_{2A}) for cropping system 1 (2). Profits for the two systems from using the lower application rate will be reduced to π_{1A} and π_{2A} respectively. Panel D shows the positive relationship assumed between profits and the leachate level up until the maximum profits for each system, π_1^* and π_2^*. The difference between these maximum unregulated profits and the profits with the environmental standard imposed represents the on-farm abatement costs. For example, with system 1, abatement costs are zero at L_1^*, which is the leachate level generated under unconstrained profit maximization (panel E). The abatement cost will be AC_{1A}, ($\pi_1^* - \pi_A^*$) for a standard set at L_A^R). Imposing a more stringent standard will increase total abatement cost. The MAC function $\lambda(w, L^R)$ is the slope of the abatement cost function in panel E.

The MAC function could also be derived explicitly with knowledge of the crop production and groundwater-N pollution functions. For example, a quadratic functional form best described both crop and pollution production functions in the alternative corn cropping systems analyzed in the following section.[1] In general notation, the yield response curve to N fertilizer rate can be expressed as:

$$Y = F(N) = a + bN + cN^2, \tag{4}$$

where a, b, and c are estimated regression coeffi-

[1] A similar maximization problem for a production system with a square-root yield-response function is presented in the appendix.

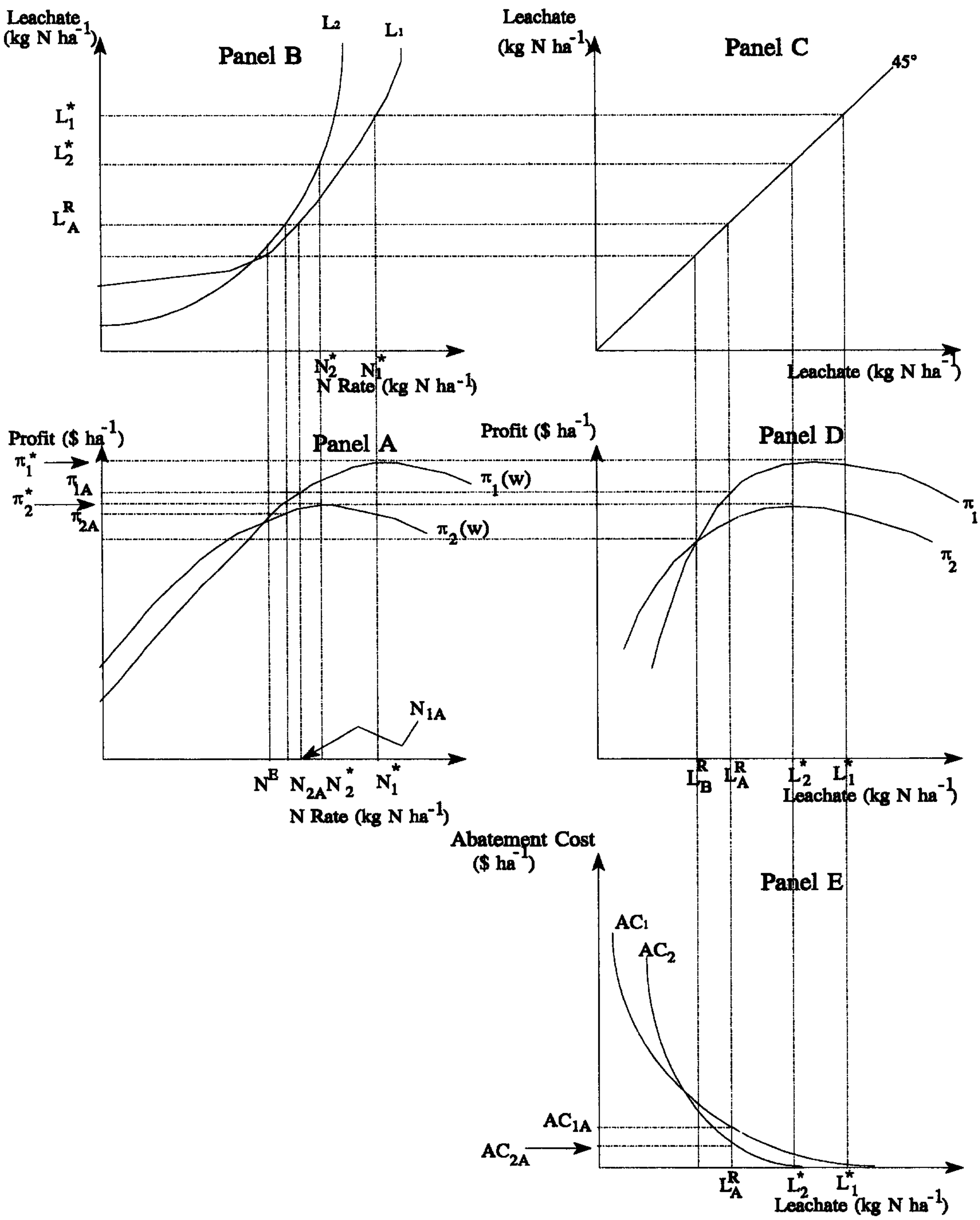

Figure 1. Evaluating Abatement Costs of Groundwater-N Pollution with Management Choices at Intensive and Extensive Margins

cients. Since yield is usually positive without any N fertilizer, and fertilizer enhances yield for initial N applications and will eventually decrease at high fertilization levels, the likely signs of the coefficients are $a > 0$; $b > 0$; and $c < 0$. These assumed signs are required for $F'(N) > 0$ and $F''(N) < 0$. Similarly, the quadratic groundwater-N pollution function can be represented as:

$$L = \alpha + \beta N + \gamma N^2, \tag{5}$$

where α, β, and γ denote the estimated regression coefficients of the pollution function. Assuming some groundwater-N leaching without any fertilizer and an increase in leaching level at an increasing rate with N suggests that $\alpha > 0$; $\beta > 0$; and $\gamma > 0$.

Substituting the quadratic output and pollution production functions into the maximization problem (equation [3]) and solving generates the following optimal N fertilizer demand:

$$(6) \quad N^R(L^R) = \frac{-1}{2\gamma}[\beta - (\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{0.5}]$$

and the marginal abatement cost function

$$(7) \quad \lambda(w, L^R) = \frac{-[-b\gamma + c\beta - c(\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{0.5} + w\gamma]}{\gamma(\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{0.5}}.$$

The shape of the MAC function can be characterized by differentiating equation (7) with respect to the environmental standard, L^R. Given the assumed signs on the production function, differentiation yields:

$$(8a) \quad \frac{\partial\lambda}{\partial L^R} = \frac{2(c\beta - b\gamma + \gamma w)}{(\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{3/2}} < 0$$

and

$$(8b) \quad \frac{\partial^2\lambda}{(\partial L^R)^2} = \frac{-12(c\beta - b\gamma + \gamma w)\gamma}{(b^2 + 4\gamma L^R - 4\alpha\gamma)^{5/2}} < 0.$$

The MAC curves decrease at an increasing rate with higher groundwater-N leachate levels. This supports the general empirical observation that it is comparatively cheap to abate initial amounts of pollution, but additional reductions require advanced expensive forms of abatement. The MAC curve that can be found as the slope of the abatement cost curve in panel E of figure 1 illustrates this property since the crop (pollution) production functions are assumed to be concave (convex).

Integration of the MAC function with respect to the leachate standard generates the abatement cost of pollution control. Abatement costs depend on the returns from the productive activities that the firm may undertake to meet any level of the environmental health objective. Differentiating equation (7) with respect to the normalized price ratio, w, yields:

$$(9) \quad \frac{\partial\lambda}{\partial w} = -\frac{1}{(\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{0.5}} < 0.$$

Thus, a higher (lower) input-output price ratio shifts the MAC curve inward (outward), implying that increases (decreases) in N fertilizer (corn) price decrease the marginal cost of environmental quality. Since profits are nonincreasing in w and MACs will reduce profits, increasing w will reduce abatement cost for a given L^R. Increasing w will shift the profit function down in panel A of figure 1 and translates to a shift in the AC curve inward in panel E.

Extensive and Intensive Management Choices

Deriving the MAC function explicitly for crop choices within a rotation is one contribution of this study. Another contribution is considering both intensive and extensive management choices when examining on-farm abatement costs for whole farming systems. Net returns for cropping system i under the extensive choice problem given earlier can be reformulated as:

$$(10) \quad \pi_i^E(w) = F_i(N_i) - wN_i - C_i,$$

where N_i is fixed and does not vary with prices. However, the intensive choice problem with N_i varying under groundwater-N regulation can be reformulated as:

$$(11) \quad \pi_i(w, L^R) = F_i(N_i(L^R)) - wN_i(L^R) - C_i.$$

Both extensive and intensive decision choice problems may be combined as:

$$(12) \quad \underset{\{X_i\}}{Max} \sum \pi_i(w, L^R) X_i + \left[L^R - \sum L_i(N_i(w, L^R)) X_i\right].$$

The decision problem for the farmer then reduces to allocating all available land to the crop choice and rotation under the tillage system (extensive choices) that, using the optimal N application rates (intensive choices), generates the highest net returns. Within each whole farming system, optimal N rates and net returns will vary according to the crop(s). However, the cost-effectiveness of an entire farming system will depend not only on the intensive choices, but also on extensive choices such as the impact of other crops in the rotation. Panel D in figure 1 shows the relative net returns for two farming systems. At the environmental quality limit L_A^R, system 1 generates higher returns than system 2. Abatement costs are generated from a discontinuous type function. Given the relative magnitudes of net returns and abatement costs as shown in panels D and E, $\pi_{1A} > \pi_{2A}$ and $AC_{1A} > AC_{2A}$. Thus, pollution abatement will have a more severe impact on system 1 than on system 2 if $\pi_1^* - AC_{1A} < \pi_2^* - AC_{2A}$. The farmer will select system 1 over system 2 even though abatement costs are higher under system 1. The optimal N rate, along with its impact on groundwater-N leaching depends on a number of other farm management practices. Thus, abatement costs will vary with each farming system. The cost effectiveness of a policy instrument in reducing groundwater-N leaching must recognize these differing abatement costs, in addition to the net returns.

Empirical Bio-economic Model

On-farm abatement costs within and among farming systems were evaluated for a representative cash crop farmer in southwestern Ontario with eight extensive management options and one intensive option (N fertilizer rate) under regulations designed to reduce groundwater-N leaching loss to the root zone. The three crops considered were corn (Zea mays L), soybeans (Glycine max L), and winter wheat (Triticum aestivum L). The alternative cropping systems analyzed included continuous corn (CC), soybean–winter wheat (SW), corn-soybean–winter wheat (CSW), and corn-corn-soybean–winter wheat (CCSW). These cropping systems represent the most popular cropping systems in the Delhi region of southwestern Ontario, after traditional tobacco. Details about the study area, along with the soil and site characteristics, are described elsewhere (Yiridoe 1997; Yiridoe, Voroney, and Weersink 1997). The tillage treatments analyzed were a conventional tillage (CT) system and no-tillage (NT). Thus, in all, eight farming systems (four crop rotations × two tillage systems) were evaluated.

The CENTURY biophysical simulation model (Metherell et al. 1993) was used to generate distribution data to predict crop production and the associated N leachate loss to groundwater for a representative farm in the Delhi region of southern Ontario. The CENTURY model was calibrated and then evaluated for its performance in predicting grain crop yields and groundwater-N leaching beyond the root zone. The evaluation was based on comparison of the modified CENTURY's predicted grain corn, winter wheat, and soybean yield response to N fertilizer application (grown in rotation), and predicted N leaching levels with actual field-measured results reported by Burton et al. (1993) and Yiridoe et al. (1993). Evaluation of the CENTURY-predicted groundwater-N leaching levels with field data on the limited farming systems for the Delhi area suggests that the predictions provide a good representation of the field N emissions beyond the root zone (Yiridoe, Voroney, and Weersink 1997). Thus, the model was used to analyze the effect of a variety of specific farm management practices on crop yields (in rotation) and environmental quality as reflected by groundwater-N pollution. Only one crop was assumed to be planted to the land allocated to each rotation for any given cropping year. For example, in the three-year CSW rotation, the cropping cycle is repeated after every three years.

Crop and Pollution Production Technologies

Crop yield response functions to N fertilizer application rate were estimated for corn and winter wheat production under several cropping systems. It was found that the concave quadratic (square root) functional form best fit the grain corn (wheat) yield distribution data. Separate functions were estimated for each crop and for each alternative tillage treatment under the various crop rotation systems. These parameter estimates are summarized in table 1.

In the estimated groundwater-N pollution production functions used (table 1), the corn and wheat groundwater-N leachate distribution data best fit two forms of the convex quadratic function, with the fertilizer rate regression coefficients (quadratic term) being negative or positive depending on the cropping system considered. A positive quadratic term implies that the convex groundwater-N leaching function rises more sharply at higher N fertilizer rates.

Farming System Costs

Crop budgets for the alternative cropping systems were adapted from actual costs of production (excluding land and labor) for the Delhi region, developed by Yiridoe et al. (1993) and the Ontario Ministry of Agriculture, Food and Rural Affairs (1994). Production costs were lower for NT systems than CT systems due largely to higher machinery costs (table 2). Among the three crops, costs of production were highest for corn production, in large part because of higher seed and variable machinery costs. In contrast, winter wheat generated the lowest costs.

Results and Discussion

Optimal Conditions with No Groundwater-N Regulation

Optimal N fertilizer rates and returns were calculated using the estimated yield response functions and average market prices. Market prices for grain corn (\$0.16 kg^{-1}), winter wheat (\$0.19 kg^{-1}), and soybeans (\$0.32 kg^{-1}) represent the Ontario provincial average for 1995, while N fertilizer price (\$0.48 kg^{-1} N) represents an average quotation

Table 1. Estimated Yield-Response and Groundwater-N Pollution Production Functions for Alternative Farming Systems

Production Function	Farming System			Estimated Production Function Coefficients			
	Crop	Tillage	Rotation	Intercept	Nitrogen (N)	N^2 ($N^{0.5}$)[a]	Adj R^2
Yield	Corn	CT	CC	2089.3 (10.69)[b]	50.67 (10.94)	−0.156 (−7.03)	0.985
		CT	CSW	2581.4 (10.46)	50.67 (8.66)	−0.150 (−5.35)	0.979
		CT	CCSW	2364.2 (8.48)	51.77 (7.84)	−0.159 (−5.05)	0.971
		NT	CC	2054.7 (11.07)	46.96 (10.68)	−0.144 (−6.84)	0.985
		NT	CSW	2399.5 (14.44)	47.73 (12.13)	−0.137 (−7.26)	0.989
		NT	CCSW	2198.6 (6.68)	48.85 (6.27)	−0.149 (−3.99)	0.956
	Wheat	CT	SW	927.47 (30.92)	−11.20 (−18.42)	284.05 (32.68)	0.998
		CT	CSW	1430.4 (36.71)	−8.98 (−11.37)	207.82 (18.41)	0.996
		CT	CCSW	1794.8 (64.99)	−6.04 (−10.78)	138.62 (17.32)	0.992
		NT	SW	1241.9 (17.63)	−7.80 (−5.47)	209.43 (10.26)	0.983
		NT	CSW	1575.0 (69.22)	−6.86 (14.88)	160.99 (24.42)	0.996
		NT	CCSW	1831.4 (51.52)	−5.19 (−7.19)	114.5 (11.11)	0.979
Pollution	Corn	CT	CC	10.11 (3.75)	−0.127 (−1.98)	0.0016 (5.31)	0.973
		CT	CSW	12.73 (6.74)	0.086 (2.92)	0.00018 (1.84)	0.958
		CT	CCSW	13.69 (4.08)	−0.016 (−1.20)	0.0008 (2.09)	0.913
		NT	CC	10.87 (2.99)	−0.18 (−2.13)	0.0025 (6.08)	0.981
		NT	CSW	10.13 (3.28)	0.119 (1.62)	0.00003 (0.77)	0.894
		NT	CCSW	13.98 (3.62)	−0.012 (1.13)	0.00087 (1.98)	0.910
	Wheat	CT	SW	10.24 (13.18)	0.14 (6.52)	0.00004 (1.37)	0.99
		CT	CSW	13.36 (16.02)	0.04 (2.49)	0.00054 (4.21)	0.985
		CT	CCSW	14.87 (35.71)	0.019 (1.52)	0.00076 (12.67)	0.998
		NT	SW	7.75 (4.07)	0.17 (4.12)	0.0002 (2.00)	0.982
		NT	CSW	13.59 (18.28)	0.073 (3.48)	0.0005 (5.23)	0.994
		NT	CCSW	14.81 (15.81)	0.019 (1.31)	0.004 (6.46)	0.988

[a]The corn yield-response to N fertilization, along with both corn and wheat pollution production functions, best fits a quadratic functional form (N^2), while the winter wheat yield-response function best fits a square-root functional form ($N^{0.5}$).
[b]Figures in parentheses are t-ratios.
Notation: CT = conventional tillage; NT = no till; CC = corn-corn rotation; CSW = corn-soybean-winter wheat rotation; CCSW = corn-corn-soybean-winter wheat rotation; and SW = soybean-winter wheat rotation.

Table 2. Total Cost of Production (Excluding Land and Labor) for Alternative Cropping Systems ($ ha^{-1})

Crop	Corn		Soybean		Winter Wheat	
Tillage	CT	NT	CT	NT	CT	NT
Variable costs						
Seed and treatment	45.21	45.21	26.75	26.75	34.2	34.20
Fertilizer[a]	—	—	—	—	—	—
Soy inoculant	—	—	7.36	7.36	—	—
Herbicide (defoliant)	0	47.81	0	55.04	0	12.98
Machinery	45.10	33.72	24.44	19.6	9.15	12.01
Other[b]	72.50	72.50	72.50	72.50	72.50	72.50
Int. on operating expenses[c]	17.91	21.92	14.42	19.94	12.74	14.49
Total variable costs	180.72	221.16	145.47	201.19	128.59	146.18
Fixed machinery cost	269.77	194.34	269.77	194.34	269.77	194.34
Total cost	450.49	415.50	415.24	395.53	398.36	340.52

[a]N fertilization was treated separately as a management choice variable in the objective function.
[b]Other includes custom hiring of combine and crop insurance.
[c]Interest on operating expenses was 11% of all other variable cost.
SOURCE: Yiridoe et al. (1993) and Ontario Ministry of Agriculture, Food and Rural Affairs (1994).

Table 3. Crop N Fertilization Rate, Yield, Returns, and N Leached by Farming System

Crop	Tillage	Rotation	N Fertilizer Rate (kg N ha^{-1})	Grain Yield (kg ha^{-1})	Profit[a] ($ ha^{-1})	N Leached (kg N ha^{-1})
Corn	CT	CC	152.79	6189	466.47	28.06
	CT	CSW	**158.90**	**6845**	**568.52**	**30.94**
	CT	CCSW	153.36	6564	526.15	30.05
	NT	CC	152.64	5868	450.05	**41.64**
	NT	CSW	**163.25**	**6540**	**552.59**	30.36
	NT	CCSW	153.86	6187	500.63	32.73
Winter wheat	CT	SW	**107.63**	**2669**	**65.07**	**25.77**
	CT	CSW	82.07	2576	59.43	20.28
	CT	CCSW	66.02	2522	56.77	19.44
	NT	SW	**103.56**	**2565**	**104.89**	27.50
	NT	CSW	74.12	2453	97.24	21.75
	NT	CCSW	55.57	2397	95.34	**28.22**
Soybean[b]	CT	SW	——	2336	320.60	9.89
	CT	CSW	——	2070	236.81	12.61
	CT	CCSW	——	2212	281.54	**14.79**
	NT	SW	——	2035	245.50	10.36
	NT	CSW	——	1563	96.82	13.29
	NT	CCSW	——	1634	119.18	**16.56**

NOTE: Figures in bold represent the highest value for each variable under the alternative tillage systems.
[a]Defined as net returns from crop production (excluding land and labor costs). Given that land and labor costs differ by farm, it was found more appropriate to calculate net returns to land and labor so that individual farms would then determine profitability for each situation.
[b]No N fertilizer was applied to soybean. Soybean grain yield and the resulting N leachate loss represent mean values predicted by the CENTURY model with N fertilizer level maintained at 90 kg N ha^{-1} for wheat and at 150 kg N ha^{-1} for corn.

from local retailers (all prices are in Canadian dollars). The optimal conditions under no groundwater-N leaching regulation for the farming systems considered are summarized in table 3. Differences in the optimal fertilizer rate, yield, and returns along with groundwater-N leachate loss between farming systems are discussed in the following sections.

Nitrogen Fertilizer Rates. The average maximum economic rate of N fertilizer application (MERN) with no N leaching regulation was 155 kg N ha^{-1} for corn and 82 kg N ha^{-1} for winter wheat production systems, which approximates the traditional rates recommended for corn (150 kg N ha^{-1}) and winter wheat (90 kg N ha^{-1}) for the study area. However, there were differences in the optimal N rate for individual farming systems depending on other management choices. Among corn production systems, optimal N fertilizer rates between rotations and tillage systems were similar for CC and CCSW rotations. With CSW rotations, N rates were 5 kg N ha^{-1} higher under CT and 10 kg N ha^{-1} higher under NT than the average, in part because of the reduced N intensive corn cycles in this rotation.

Tillage had no impact on fertilizer rate to corn except in the CSW rotations. Differences in the average N rate between cropping systems were greater for wheat than for corn production systems. N fertilizer rates were greater under CT than under NT among wheat farming systems, supporting Halvin et al.'s hypothesis (1990) that NT regimes, which tend to accumulate crop residues on the surface, result in higher concentrations of organic carbon and nitrogen than do CT regimes. Under this situation, the CT wheat production systems will require greater mineral N additions to meet crop N requirements. Optimal N fertilizer rates on wheat decreased with frequency of corn in the rotation, suggesting that the higher rate of decay of the non-corn (relative to the corn) crop residues (Woods and Edwards 1992) may account for part of the growing-crop N requirements.

Crop Yields and Net Returns. Profit-maximizing grain corn[2] and wheat yields were obtained by substituting the optimal N fertilizer levels into the appropriate production functions (table 3). Net returns to crop production (excluding land and labor cost) were then determined for each crop under the alternative management practices. Rotation effects indicate the influence of extensive management

[2] Corn production function under CCSW rotations was estimated from mean yield data for the first- and second-year production cycles. It generated a corresponding N pollution function that represents an average of the two periods, stabilizing over the long run. In general, first-year grain corn yields were higher than second-year yields, in part because of previous crop effects.

choices on the optimal N fertilizer rate and hence highlight the need to estimate a production function for each farming system. For example, although CC and CCSW rotations generated similar N fertilizer levels, yields were lower for CC, in part because of N-rotation credits from previous crops in CCSW rotations. CT systems generated higher yields than NT systems for all three crops. Differences in corn yield due to tillage effect were highest under CCSW rotations (by 377 kg ha^{-1}) and lowest under CC rotations (by 321 kg ha^{-1}). CSW-CT generated the highest net returns (\$569 ha^{-1}) among the corn production systems. In contrast, CC-NT generated the lowest profits (\$450 ha^{-1}). The most profitable rotation for wheat and soybeans was a SW rotation.

Groundwater-N Leached. Groundwater-N leachate levels were higher than the Health Canada maximum contaminant limit (MCL) (10 mg N ha^{-1} translates to 15.2 kg N ha^{-1}) for all twelve cropping systems (table 3). Groundwater-N leachate losses were similar among the twelve cropping systems except for continuous corn under NT, which had a markedly higher N leaching loss (42 kg N ha^{-1} per year). The high N leaching loss associated with this system is because the total amount of NO_3^--N in the soil profile that is vulnerable to leaching is directly related to frequency of corn in the rotation and level of crop residue on the surface (Olsen et al. 1970).

Although average groundwater-N leaching levels were greater under corn production (32 kg N ha^{-1}) than under winter wheat production systems (24 kg N ha^{-1}), leachate levels for wheat systems were also above the Health Canada MCL. Among wheat production systems, CT treatments generated lower N leaching levels than did corresponding NT systems because of the effects of crop residue under NT systems in increasing water drainage and leaching loss. In addition, the effect of an additional corn cycle to the CSW rotation on increased groundwater-N leaching loss was higher under NT than under CT. As a result, CCSW-NT generated the highest nitrate leachate level among the wheat production systems.

The results suggest that systems with the highest N fertilizer rates do not necessarily generate the highest leaching losses, supporting Burton et al.'s hypothesis (1993) that crop rotation pattern can be used to mitigate potential consequences of high nitrate contamination. This finding also has implications for groundwater-N leaching reduction in that improved grain yields and returns may be obtained without necessarily generating high levels of pollution from N fertilizer use by selecting the appropriate crop rotation system.

Marginal Abatement Cost at the Intensive Margin

Marginal abatement costs (MACs) associated with the alternative crop production systems were calculated by substituting the specific yield and pollution function regression parameters into the general relationships derived in equation (7), while varying the contaminant limit, L^R, below and above the Health Canada MCL. MAC curves associated with the individual cropping systems are presented in figure 2 for corn and in figure 3 for winter wheat production systems. The MAC curves are convex and negatively sloping, consistent with the theory developed earlier.

Among wheat production systems, MAC of reducing nitrate leaching to the Health Canada MCL were generally lower compared with corn and ranged from \$6 ha^{-1} (SW-NT) to \$61 ha^{-1} (CCSW-CT). SW-NT generated the lowest MAC, up until an MCL of 10% above the Health Canada standard. Above this point, CCSW-CT generated the lowest MAC of pollution reduction. NT treatments resulted in lower MACs with SW rotations, as the standard was varied. In contrast, CT generated lower MACs with CSW rotations. The results suggest that cropping sequence had a greater effect on magnitude of MAC than did tillage.

The MAC curves in figure 2 and 3 suggest that differences in MACs between crop rotations are greater at lower levels of N pollution than at higher levels. Thus, the explicit MAC curves generated suggest that management choices at the intensive (extensive) margin may be more (less) effective in mitigating groundwater-N pollution under high MCLs. At high MCLs, crop choice and cropping patterns are less important for mitigating nitrate pollution, so adjusting other farm management choices at the intensive margin, such as N fertilization, may be more useful. This hypothesis is consistent with Yiridoe, Voroney, and Weersink's finding (1997) that relative reduction in mineral N leachate level is markedly greater when fertilizer is applied at rates above the maximum economic rate of N fertilization (MERN) than below the MERN.

Cost-Effective Corn and Wheat Crop Production Systems

With Standards Set to Meet the Health Canada MCL. Net returns and on-farm abatement costs of reducing groundwater-N pollution to the Health Canada standard are summarized for corn and for wheat farming systems (table 4). The corn farming system that had the lowest abatement cost and also generated the highest net returns under both tillage treatments was CCSW-CT. With the Health

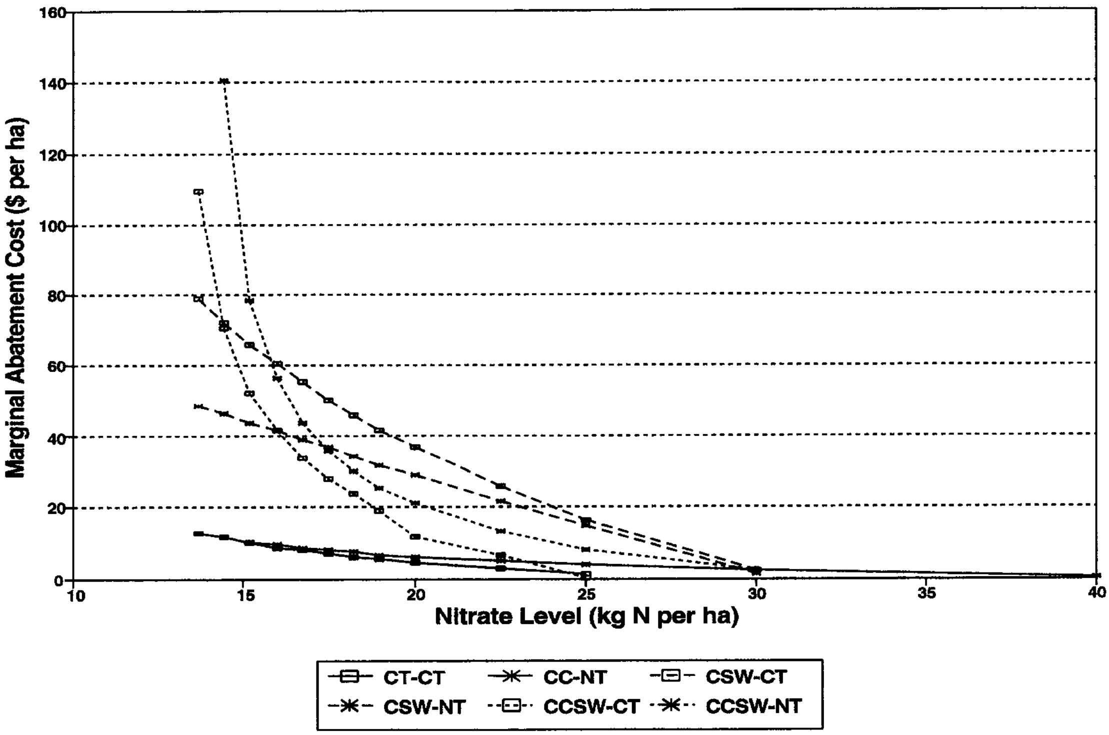

Figure 2. Marginal Abatement Costs for Corn Farming Systems with Alternative Management Choices at the Intensive Margin

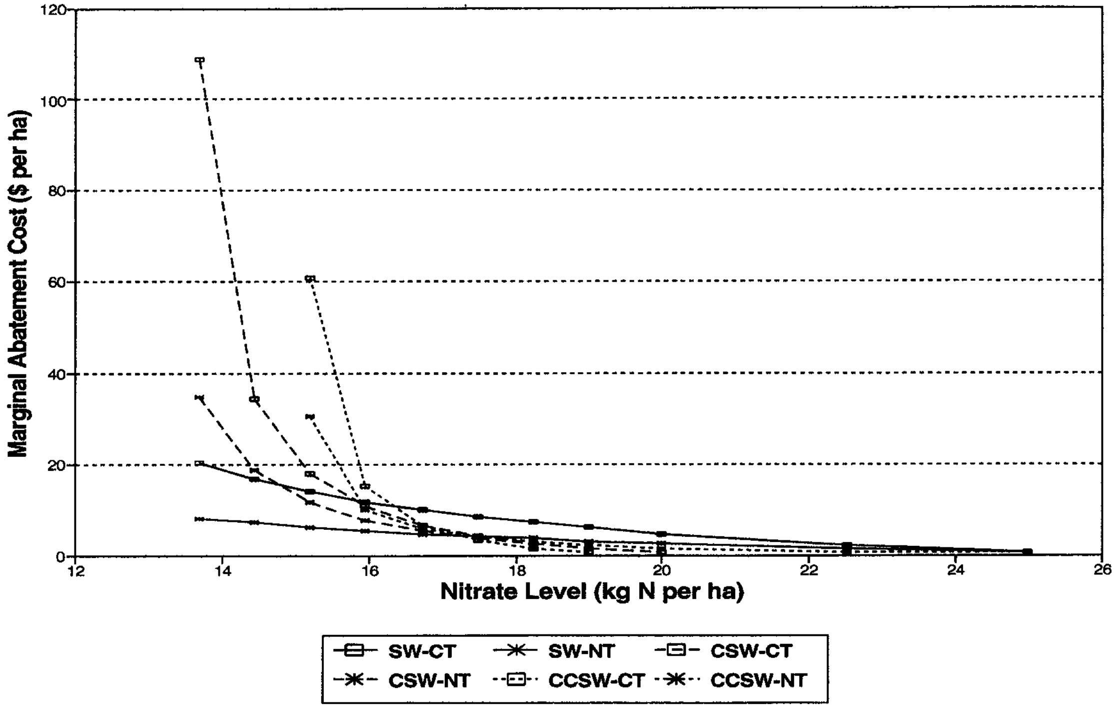

Figure 3. Marginal Abatement Costs for Winter Wheat Farming Systems with Alternative Management Choices at the Intensive Margin

Table 4. Farm Returns and Abatement Costs for Corn and Wheat Farming Systems under Alternative Management Choices at the Intensive Margin (\$ ha^{-1})

Groundwater-N Leaching Limit (kg N ha^{-1})		Conventional Tillage			No-Tillage		
		CC	CSW	CCSW	CC	CSW	CCSW
	13.68	54.91 (481.65)[a]	42.11 (526.41)	69.24 (456.91)	84.35 (436.71)	161.11 (391.47)	r.c.[b]
	15.20[c]	205.98 (260.49)	152.11 (416.40)	277.90 (248.25)	165.78 (284.27)	231.19 (321.40)	217.96 (282.67)
	16.72	313.62 (196.07)	243.90 (324.62)	359.18 (166.97)	217.50 (280.71)	293.98 (258.61)	305.72 (194.91)
Corn	18.24	420.68 (94.18)	320.38 (248.13)	410.98 (115.17)	377.69 (126.01)	349.61 (202.98)	360.57 (140.06)
farming	19.00	441.89 (45.07)	353.55 (214.96)	430.63 (95.52)	389.82 (69.98)	374.81 (177.78)	381.50 (119.13)
systems	20.00	450.84 (15.64)	392.62 (175.90)	451.98 (74.17)	400.66 (49.39)	405.31 (147.28)	404.54 (96.10)
	22.50	459.62 (6.85)	469.90 (98.61)	489.52 (36.63)	414.07 (35.98)	468.66 (83.93)	446.25 (54.38)
	25.00	464.54 (1.93)	522.26 (46.25)	511.44 (14.71)	424.54 (25.52)	513.92 (38.66)	472.73 (27.90)
	30.00	465.78 (0.69)	567.47 (1.05)	526.15 (0.00)	438.85 (11.20)	552.42 (0.17)	497.70 (2.93)
	40.00	r.c.	449.87 (0.19)	r.c.	r.c.	r.c.	r.c.
		SW	CSW	CCSW	SW	CSW	CCSW
	13.68	−13.01 (78.09)	−30.18 (89.626)	r.c.	66.69 (38.20)	−4.25 (101.50)	r.c.
	15.20	12.67 (52.40)	33.90 (25.54)	20.52 (36.25)	77.47 (27.42)	65.59 (31.66)	63.05 (32.29)
Wheat	16.72	30.51 (34.56)	50.73 (8.70)	50.63 (6.14)	85.57 (19.32)	84.02 (13.23)	81.74 (13.59)
farming	18.24	43.20 (21.87)	57.22 (2.21)	55.97 (0.80)	91.70 (13.20)	92.28 (4.96)	87.76 (7.58)
systems	19.00	48.11 (16.97)	58.65 (0.79)	56.67 (0.09)	94.16 (10.73)	94.56 (2.68)	89.57 (5.77)
	20.00	53.34 (11.73)	59.40 (0.03)	r.c.	96.90 (7.99)	96.39 (0.86)	91.30 (4.04)
	22.50	61.69 (3.38)	r.c.	r.c.	101.68 (3.21)	r.c.	93.82 (1.52)
	25.00	64.90 (0.17)	r.c.	r.c.	104.16 (0.74)	r.c.	94.94 (0.40)
	30.00	r.c.	r.c.	r.c.	r.c.	r.c.	r.c.

[a]On-farm abatement cost (\$ ha^{-1}) is in parenthesis.
[b]The notation r.c. implies that the groundwater-N restriction was a nonbinding constraint. Consequently, the (least cost) optimal conditions will be as occur under no groundwater-N regulation.
[c]Health Canada MCL for nitrates is equivalent to 15.2 kg N ha^{-1}.

Canada nitrate pollution restriction, returns for CCSW-CT exceeded the next best alternative (CC-CT) by \$72 ha^{-1}. In contrast, CSW rotations generated the lowest returns and the highest abatement costs despite being the most profitable corn production system under no pollution regulation (table 3). The reason for the change is that the yield response function or pollution function is more responsive to changes in N fertilization rate for CSW than for the other rotations. For example, the improvement in groundwater-N quality to the Health Canada standard was achieved under CCSW-CT by reducing optimal N fertilizer rate by 64% and subsequently corn yield by 28%. In contrast, optimal N fertilization rate and yield decreased by 83% and 44%, respectively, under CSW-CT. A yield reduction of this magnitude is unlikely to be acceptable to farmers.

Among the wheat production systems, CSW rotation generated the lowest abatement cost (\$26 ha^{-1}) and the highest returns (\$34 ha^{-1}) at the Health Canada standard under CT systems (table 4). Under NT, SW was the most cost-effective system with the highest net returns (\$78 ha^{-1}) and lowest on-farm abatement cost to the producer (\$27 ha^{-1}). SW-CT was the most negatively impacted upon by the groundwater-N quality regulation. This finding underscores the need to evaluate both net returns and abatement costs for policy decision-making. The lowest cost wheat production system for reducing groundwater-N leaching loss is to shift to a noncorn (less N-intensive) crop rotation system, consistent with Johnson, Adams, and Perry's analysis (1991) of the least-cost method of reducing N pollution for potato, alfalfa, and grains crops. In a similar analysis, Swinton and Clark (1994) found a substitution of less N-intensive soybean crops for corn with tighter pollution restrictions.

Under Alternative Groundwater-N Standards. In general, returns were highest under less N-intensive rotations with stringent pollution-standards and were highest for CCSW rotations among corn production systems (table 4). At $L^R \leq$ 16.72 kg N ha^{-1}, the most cost-effective corn farming system was CCSW-CT, which consistently generated the highest profits and lowest abatement cost. CC-CT generated the lowest abatement cost with relaxed (higher) leachate restrictions ($L^R \geq$ 18.24). Thus, more stringent restrictions on leaching had the lowest impact on CCSW-CT, among the corn production systems. However, less stringent restrictions on pollution had the lowest impact on CC-CT rotation. Among corn production systems, relative ranking of the level of abatement cost seems to correlate inversely with relative ranking in profitability at low environmental standards. At higher standards ($L^R > 20$ mg N ha^{-1}), there was not necessarily a direct correlation between abatement cost and returns. Thus, relative ranking of the corn production systems depended on the standard considered.

The effect of tillage on relative ranking of the level of abatement cost depended on the rotation. For example, NT systems generated higher abatement costs under CC and CCSW rotations, while CSW rotations generated higher abatement costs under CT as the standard was varied. Although tillage did not have a consistent trend on profitability across standards, at lower nitrate limits (with $L^R < 20$ mg N ha^{-1}), CT treatments were more cost-effective than were NT systems under CC and CCSW rotations. In contrast, NT systems were more cost-effective than were CT for CSW rotations.

Among wheat production systems, SW-NT ranked first in profitability under the various restrictions on N leaching (table 4). In contrast, SW-CT generated the lowest returns under the standards considered. NT systems generated higher returns than the corresponding CT systems. SW-CT consistently generated the highest on-farm abatement cost as the groundwater-N restriction was varied. The only exception was when the leaching restriction was set at 13.68 kg N ha^{-1}, in which it ranked third. Relative abatement cost ranking among the remaining systems depended on the standard. The effect of tillage on abatement costs also depended on the rotation. NT generated high abatement costs under CSW rotations. In contrast, CT generated higher abatement costs under SW rotations.

Cost-Effective Whole Farming System

In the preceding section, the cost-effective corn and wheat production technologies were analyzed under the alternative corn and wheat crop production systems. In this section, net returns and abatement costs were generated for all the crops within each crop rotation system, with decision choices at both the intensive and the extensive margins. The purpose was to determine the most profitable of the eight farming systems that would be allocated to all the land resource base ($\bar{X} = 1$) under a given environmental quality standard. In the first part of this section, cost-effectiveness is evaluated under peak nitrate leaching conditions in which N leachate is assumed to be associated with the individual corn and wheat crops within each crop rotation system.

However, in reality a multicrop rotation should allow some abatement to occur through other crops in the cropping system. Given that no N fertilizer is normally recommended for soybean crops, there were no smooth N leachate loss production curves estimated (as a function N fertilization) for the soybean production systems. In the first part of this section, the objective of allocating all the available land resource to the most profitable whole farming system was examined with the assumption that there was no environmental constraint imposed on the soybean production technologies. Although N leaching loss associated with the soybean production systems, due mainly to inherent soil N, may be less of a concern compared with N contamination resulting from crops to which N fertilizer is applied, the analysis below could exaggerate N leaching loss from systems where corn is rotated with crops that leach less than corn. To evaluate this possibility, the same whole farming systems were analyzed with "average" N leachate levels in which a given multicrop rotation system allows for some abatement to occur through other crops in the rotation. For example, with the Health Canada MCL restriction, an "average" N leachate restriction is imposed on the whole farming system under a CC rotation, similar to that for the individual corn crops in the rotation ($L^R = 15.2$ kg N ha^{-1}). However, the average N leachate level associated with an SW rotation would require double the leachate level (i.e., 30.4, or 2 × 15.2 kg N ha^{-1}) from the wheat crop since it was assumed that no N leaching loss from N fertilization resulted from soybean production. In other words, the soybean crop is assumed to mitigate, at least in part, the high level of N leachate (30.4 kg N ha^{-1}) associated with the wheat crop. Results of the cost-effective farming system under average N leaching for all the crops under each of the eight systems follow the analysis under peak N leaching conditions.

Under Peak N Leachate Loss. Net returns and on-farm abatement costs for whole farming systems are summarized in table 5. With no environmental regulation, continuous corn under CT was the most profitable farming system, followed by CC-NT. In contrast, SW farming systems generated the lowest profits. Average corn yields were 2.5 (3.2) times greater than wheat (soybean) yields (table 2), so differences in profitability ranking with no constraints on groundwater quality to the farmer were influenced by the differences in grain yields. In addition, the yield response functions for the CC rotations were relatively flat for the range within the optimal N fertilization rates. Thus, reductions in N rate as the standard was tightened

Table 5. Net Returns and Abatement Costs (AC) under Alternative Farming Systems with Management Choices at Both Intensive and Extensive Margins (\$ ha^{-1})

Groundwater-N Leaching Limit (kg N ha^{-1})	Farming Systems															
	Conventional Tillage								No-Tillage							
	CC		SW		CSW		CCSW		CC		SW		CSW		CCSW	
	Profit[a]	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC
0	466.47		192.84		358.32		347.65		450.05		175.20		324.81		303.95	
13.68	57.91 (88)	408.56	153.80 (20)	39.04	72.71 (78)	285.61	119.20 (66)	229.46	84.35 (81)	365.70	156.10 (11)	19.10	103.70 (68)	221.11	r.c.[b]	r.c.
15.20[c]	205.98 (56)	260.49	166.64 (14)	26.20	143.73 (59.89)	214.59	214.47 (38)	133.19	165.78 (63.16)	284.27	161.49 (8)	13.71	156.20 (51.91)	168.61	154.54 (49)	149.41
16.72	313.62 (33)	152.85	175.56 (9)	17.28	193.84 (46)	164.49	262.63 (25)	85.02	217.50 (52)	232.55	165.54 (6)	9.66	192.20 (41)	132.61	203.09 (33)	100.86
18.24	420.68 (10)	45.79	181.90 (6)	10.94	233.70 (35)	124.62	289.87 (17)	57.78	377.69 (16)	72.36	168.60 (4)	6.59	222.08 (32)	102.73	232.02 (24)	71.92
19.00	441.89 (5)	24.58	184.36 (4)	8.48	250.64 (30)	107.68	299.87 (14)	47.78	389.82 (13)	60.23	169.83 (3)	5.37	235.25 (28)	89.56	242.94 (20)	61.01
20.00	450.84 (3)	15.63	186.97 (3)	5.86	270.36 (25)	87.96	310.54 (11)	37.12	400.66 (11)	49.39	171.20 (2)	4.00	250.96 (23)	73.85	254.89 (16)	49.05
22.50	459.62 (1.5)	6.85	191.15 (0.9)	1.69	309.01 (14)	49.31	329.34 (5)	18.32	414.07 (8)	35.98	173.59 (0.9)	1.60	282.85 (13)	41.96	276.38 (9)	27.57
25.00	464.54 (0.4)	1.93	192.75 (0.04)	0.09	335.19 (6)	23.13	340.30 (2)	7.35	424.54 (6)	25.51	174.83 (0.2)	0.37	305.48 (6)	19.34	289.90 (5)	14.05
30.00	r.c.	—	r.c.	—	357.80 (0.15)	0.52	r.c.	—	438.85 (2.5)	11.20	r.c.	—	324.73 (0.03)	0.09	302.48 (0.5)	1.46
40.00	r.c.	—	r.c.	—	r.c.	—	r.c.	—	449.87 (0.04)	0.18	r.c.	—	r.c.	—	r.c.	—

[a]Percentage reduction in net returns from net returns under no pollution regulation in parenthesis.
[b]The notation r.c. implies that the groundwater-N restriction was a redundant constraint. Consequently the (least cost) optimal conditions will be as occur under no groundwater-N regulation.
[c]Health Canada MCL for nitrates is equivalent to 15.2 kg N ha^{-1}.

generated less than proportionate reductions in yield and hence profits. Consequently, continuous corn systems generated higher profits than did farming systems with only soybean-wheat crops in the rotations. An interesting finding was that the SW rotations were the most profitable systems when the pollution restriction was set at 13.68 kg N ha^{-1}. The N-intensive rotations involving corn are unprofitable at very low MCLs.

Environmental standards set at the Health Canada MCL had the greatest adverse effect (in terms of reduction in net returns) on CC farming systems under NT (table 5). In contrast, SW-NT had the lowest negative impact. As a result, the on-farm abatement cost was highest under CC-NT (\$284 ha^{-1}) and lowest under SW-NT (\$14 ha^{-1}). In contrast to the results under no environmental regulation, CCSW-CT was the most profitable farming system that meets the Health Canada standard. On-farm abatement cost reduced CCSW-CT returns by 38%. The adverse impact of the environmental constraint resulted in CSW-CT generating the lowest net returns (\$144 ha^{-1}), a shift from SW-NT in the unregulated scenario.

As the environmental standard was varied above the Health Canada MCL, CC-CT consistently generated the highest profits. Yet the same farming system was not the least adversely affected by the groundwater pollution control standards. For example, with standards set at ($L^R \geq 19.00$ kg N ha^{-1}), percentage reductions in net returns were similar for SW-CT, SW-NT, and CC-CT. Thus, the earlier hypothesis that profitability ranking among farming systems is influenced, in large part, by differences in system yields is consistent with this finding. Although abatement costs reduced net returns, farming systems with higher crop yields more than made up for pollution control costs.

Under Average N Leaching Conditions. Results of the impact of average N leaching loss on the cost-effective whole farming system under the alternative farming systems considered are presented in table 6. Analyzing cost-effectiveness using average N leached for whole farming systems (resulting in higher N leaching from the associated corn and wheat crops in the multicropping systems) further makes the CC systems unprofitable at slightly higher average N pollution levels ($L^R \leq 16.72$ kg N ha^{-1}) than in the preceding analysis. For example, the cost-effective system to allocate all the land with standards set to meet the Health Canada MCL for whole farming systems was a CCSW-CT, followed by the three-year CSW-CT rotation. In contrast, the two CC rotations ranked the lowest in cost-effectiveness. The CC rotations generated the highest cost-effectiveness ranking at slightly higher average N pollution standards ($L^R \geq 18.24$ kg N ha^{-1}). Thus, consideration of systems where corn is rotated with crops that leach less than corn generates higher net returns and lower abatement costs than the results summarized in table 5 suggest.

Policy Implications

The results provide several useful insights for both farmers and policymakers. The key issue underlying the policy implications or usefulness of the results concerns minimizing both environmental and abatement costs. On-farm abatement cost estimates are important particularly in watersheds with small overall off-farm net benefits. In that case, if there are significant net costs to farmers, the decision may tilt in favor of maintaining the status quo, rather than abate. Moreover, the abatement cost estimates are likely to be the upper bounds associated with the individual farming systems analyzed because of the possibility of discovering cost-saving technologies from enforcing tighter pollution standards. Porter and van der Linde (1995) noted that unforeseen technological innovations in groundwater-N pollution control or prevention can also generate lower abatement costs than previously envisaged.

Another policy implication of the MAC results stems from the fact that many agricultural pollution control programs involve cost-sharing initiatives (between farmers and a pollution control agency). Under such circumstances, the agency will need to know the level of payment and the specific farmers who should benefit from the payment program in order to encourage producers to adjust their farming practices. Accurate knowledge of farming system-specific MAC functions is essential in this regard, since higher abatement costs associated with particular farming systems will require higher incentives in order to encourage producers to adjust their production practices.

Implementing the cost-effective farming system that meets the Health Canada standard requires accurate crop yield and pollution production functions in order to determine the optimal N fertilization rates. In turn, this requires an effective system to monitor farmers' compliance to the recommended N application rates. Incorporating monitoring costs adds a further dimension to this multistage, simultaneous issue, where compliance to the recommended rates may require reevaluating the cost-effective cropping systems. The cost of monitoring compliance is a technical issue involving an analysis that is beyond the scope of the present study.

Table 6. Net Returns and Abatement Costs (AC) with Average N Leaching Conditions under Alternative Farming Systems ($ ha−1)

Average Groundwater-N Leaching Limit Imposed on Whole Farming System (kg N ha^{-1})	Farming System															
	Conventional Tillage								No-Tillage							
	CC		SW		CSW		CCSW		CC		SW		CSW		CCSW	
	Profit[a]	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC	Profit	AC
0	466.47		192.84		358.32		347.65		450.05		175.20		324.81		303.95	
13.68	57.91 (13.68)	408.56	192.80 (27.36)	0.04	272.41 (20.52)	85.91	289.87 (18.24)	57.78	84.35 (13.68)	365.70	r.c.[b] (27.36)	—	255.02 (20.52)	69.79	232.02 (18.24)	71.92
15.20[c]	205.98 (15.2)	260.49	r.c. (30.40)	—	312.07 (22.8)	46.25	312.10 (20.27)	35.55	165.78 (15.2)	284.27	r.c. (30.40)	—	284.19 (22.80)	40.62	257.01 (20.27)	46.94
16.72	313.62 (16.72)	152.85	r.c. (33.44)	—	338.97 (25.08)	19.35	327.41 (22.29)	20.24	217.50 (16.72)	232.55	r.c. (33.44)	—	307.14 (25.08)	17.67	274.47 (22.29)	29.48
18.24	420.68 (18.24)	45.79	r.c. (36.48)	—	341.01 (27.36)	17.31	338.94 (24.32)	8.67	377.69 (18.24)	72.36	r.c. (36.48)	—	315.94 (27.36)	8.87	287.35 (24.32)	16.60
19.00	441.89 (19.00)	24.58	r.c. (38.00)	—	348.50 (28.50)	9.82	342.03 (25.33)	5.62	389.82 (19.00)	60.23	r.c. (38.00)	—	r.c. (28.50)	—	293.20 (25.33)	10.75
20.00	450.84 (20.00)	15.63	r.c. (40.00)	—	357.80 (30.00)	0.52	r.c. (26.67)	—	400.66 (20.00)	49.39	r.c. (40.00)	—	250.96 (30.00)	—	295.95 (26.67)	8.00

[a]Figures in parentheses represent individual environmental quality restrictions. L^R, imposed on corn and wheat.
[b]The notation r.c. implies the groundwater-N restriction was a redundant constraint. Consequently the (least cost) optimal conditions will be as occur under no groundwater-N regulation.
[c]Health Canada MCL for nitrates is equivalent to 15.2 kg N ha^{-1}.

Summary

Knowledge of the characteristics of MAC functions is necessary to determine how farmers can cost-effectively adjust their production practices in order to meet pollution regulation objectives. The study found that because the maximum economic rate of N fertilization and the level of groundwater-N leaching loss depend on a variety of farm management practices, such as crop choice, crop rotation, and tillage treatment, on-farm abatement costs also varied with the farming systems. Without any regulation, groundwater-N leachate levels were higher than the Health Canada MCL for all the farming systems considered. Systems that required the highest optimal N fertilizer rates did not generally result in the highest leaching losses, implying that crop rotation pattern can be used to mitigate potential consequences of high nitrate contamination. It is important to note that these results are sensitive and highly dependent on crop prices. For example, soybean acreage has increased tremendously in recent years in response to increased prices.

The explicit MAC curves generated support the conventional wisdom that choice of a cost-effective farming system for mitigating nitrate leaching is more critical under more stringent standards than at higher pollution levels. Differences in MACs among farming systems are more significant under more stringent standards (lower leachate levels). At high pollution levels, crop choice and cropping pattern are less important, so adjusting other farm management practices, such as choices at the intensive margin, may be more useful.

The cost-effective corn production system, which meets the Health Canada MCL, with the highest returns and lowest on-farm abatement costs of groundwater-N leaching regulation was a four-year CCSW rotation under CT. Among wheat production systems, SW-NT generated the highest returns and the lowest abatement costs in order to meet the Health Canada standard. At MCLs above the Health Canada standard, the cost-effective wheat farming system shifted from SW-NT to CSW-NT. The results highlight the importance of decomposing the elements of the abatement cost function for each farming system, involving pollution production and yield response functions. Knowledge of these system-specific abatement costs is particularly relevant under a cost-sharing initiative between farmers and a pollution control agency in which the agency needs to base any incentive packages to farmers on accurate information about the MACs associated with particular farming systems.

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Appendix: MAC Curve with a Square Root Wheat Production Functional Form

The maximization problem for wheat production systems with square-root yield response functional forms is represented as:

$$\text{(A1)} \quad \underset{\{N,\lambda\}}{Max}\ \pi^R = (a + bN + cN^{1/2}) - wN + \lambda\,[L^R - (\alpha + \beta N + \gamma N^2)],$$

where $a > 0$, $b < 0$, and $c > 0$ represent the regression coefficients for the wheat production function; α, β, and γ denote regression coefficients for the corresponding groundwater-N leaching function. Solving the first-order conditions simultaneously for λ yields the MAC function:

$$\text{(A2a)} \quad \lambda\,(w, L^R) = \frac{-\left[b + 1/2 \dfrac{c}{\left[\dfrac{-1}{2\gamma}\left(\beta - (\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{1/2}\right)\right]^{1/2}} - w \right]}{-\beta - 2\gamma\left[\dfrac{-1}{2\gamma}\left(\beta - (\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{1/2}\right)\right]},$$

which can be reduced to:

$$\text{(A2b)} \quad \lambda\,(w, L^R) = \frac{-\left[\left(b + \frac{1}{2}\left(\dfrac{c}{\eta^{1/2}}\right)\right) - w\right]}{-(\beta + 2\gamma\eta)},$$

where $\mu = (\beta^2 + 4\gamma L^R - 4\alpha\gamma)^{0.5}$ and $\eta = \frac{-1}{2\gamma}(\beta - \mu)$. Under varying MCLs ($L^R$), the on-farm abatement cost per unit area, representing the area under the MAC curve, can be estimated for each cropping system by integration.