Risk Considerations in the Reduction of Nitrogen Fertilizer Use in Agricultural Production

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Nonpoint pollution problems resulting from current agricultural practices are forcing policymakers to examine alternative mitigation strategies. Two mechanisms suggested to control the use of nitrogen fertilizer, a source of potentially harmful contaminants of water sources, are quantitative standards and incentives through per-unit taxation. Impacts of both policies on the distribution of farm net returns are analyzed. Risk attitudes are observed to influence the magnitude of farmer response to alternative policies.

Key words: nitrogen fertilizer, production functions, risk, nonpoint pollution.

Society is becoming increasingly concerned with agricultural use of scarce resources and the industry's contribution to the pollution of air, land, and water. Recent focus has been on the use of agricultural chemicals and inorganic fertilizers and their impacts on surface and groundwater quality (St. Onge). Groundwater supplies in as many as 50% of the counties in the contiguous United States are threatened by farm runoff (Nielsen and Lee). Over 100 million people live in these areas of potential groundwater contamination (Nielsen and Lee). There has been an increase in policies designed to limit agricultural nonpoint source pollution as a result of increased awareness of the potential problems resulting from farm fertilizer and chemical use (Batie).

Although the analysis of firm and industry impacts of alternative control policies is well developed under certainty (Stevens; Baumol and Oates), few studies have been undertaken investigating quantitative effects of policies on the distributions of farm net returns. The purpose of this article is to develop and report the results of a model to measure farm income and risk impacts resulting from both an input tax and quantitative use restrictions designed to reduce nitrogen application rates.

Although mandated changes in input use may change expected net returns (Ayer et al.), changes in input use will have uncertain impacts on the variability of yields and, consequently, on the variability of net income. It is thus important to identify not only impacts on expected farm income but also to consider induced changes in income variability. Reducing nitrogen use, for example, may reduce income variability. The loss to the risk-averse producer may be overestimated if variability effects are ignored.

As Shortle and Dunn noted, policy analyses of practical interest will investigate ambient pollution goals in an industry composed of more than one firm and having alternative production technologies. However, the outcome of control policies will depend upon the response they elicit at the individual firm level. This article contributes to the literature by exploring firm level responses when risk is present and important to the individual decision maker. A preliminary investigation of aggregate responses also is modeled. Aggregate response to different control policies is reported for three firms having identical production technologies and facing the same prices, differing only by risk aversion characteristics of the decision maker.

Production functions for four Arizona crops

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Table 1. Coefficients from the Three-Stage Estimation of the Just-Pope Production Function: $y = Ax_W^{\alpha_W}x_N^{\alpha_N} + Bx_W^{b_W}x_N^{b_N} + \epsilon$

A	α_W	α_N	B	b_W	b_N
357.950 (182.830)	0.265 (.093)	0.174 (.058)	9.379 (2.551)	−0.226 (.545)	−0.496 (.244)

Note: Standard errors are in parentheses.

are estimated under different combinations of water and nitrogen inputs. Just-Pope type production functions are estimated to allow the isolation of impacts of changing input use on both expected yields and on the variance of yields. Output prices are treated stochastically in the model. Thus, gross returns are the product of both random yields and prices. Impacts are assessed at different levels of producer risk aversion.

The next section of this article examines the properties of the Just-Pope type production function and addresses the role of uncertainty in determining input use. Coefficients of the production model are estimated for cotton using Arizona data. Farm impacts of an input tax and of quantity controls on fertilizer use are calculated and compared. The model is expanded to allow diversification among four crops as a response to changing policies. The final empirical section presents a preliminary application of the model in a multiple farm framework, where impacts of use restrictions on three farms characterized by managers having different risk attitudes are investigated. The article concludes with a summary and discussion of additional applications of the model in a broader geographic perspective.

Model—Single Crop

The single-crop production function can be estimated:

$$(1) \qquad y = f(x_N, x_W) + h^{1/2}(x_N, x_W) + \epsilon,$$

where y is per-acre yield and x_N and x_W are inputs of nitrogen and water, respectively. The stochastic error term, ϵ, is assumed to be distributed $\sim N(0, 1)$. Following Just and Pope, the production equation can be decomposed into deterministic and stochastic elements:

$$E(y) = f(x_N, x_W), \text{ and}$$
$$\sigma_y^2 = h(x_N, x_W),$$

where $E(y)$ is the expected yield and σ_y^2 is variance of yield.

Under random price, p, known costs, r_N and r_W, and variable costs other than for water and nitrogen, VC, per-acre profit will be

$$(2) \qquad \pi = py - r_N x_N - r_W x_W - VC.$$

Expected profit will be

$$(3) \qquad E(\pi) = E(py - r_N x_N - r_w x_W - VC) = \bar{p}f(x_N, x_W) + \sigma_{py} - r_N x_N - r_W x_W - VC,$$

where bars over variables represent expected values. The distributions of price and quantity are assumed independent for the individual producer, so the covariance term in (3) equals zero.

Variance of profit, when both p and y are random and independent, will be (Mood, Graybill, and Boes):

$$(4) \qquad \mathrm{Var}(\pi) = \bar{y}^2\sigma_p^2 + \bar{p}^2\sigma_y^2 + \sigma_p^2\sigma_y^2 = [f(x_N, x_W)]^2\sigma_p^2 + \bar{p}^2[h(x_N, x_W)] + \sigma_p^2[h(x_N, x_W)].$$

Robison and Barry approximated the certainty equivalent of per-acre profit by:

$$(5) \qquad CE = E(\pi) - \lambda/2\ \mathrm{Var}(\pi),$$

where λ is the value of the Pratt-Arrow absolute risk aversion function. Optimal input decisions for the maximization of (5) can be found by solving the following nonlinear programming problem:

$$(6) \qquad \max_{x_N, x_W} CE = \bar{p}f(x_N, x_W) - r_N x_N - r_W x_W - VC - \lambda/2\{[f(x_N, x_W)]^2\sigma_p^2 + \bar{p}^2 h(x_N, x_W) + \sigma_p^2 h(x_N, x_W)\},$$

subject to

$$l_i \le x_i \le u_i \qquad \text{for } i = N, W.$$

Table 2. Selected Results of Adjusting λ under Initial Cost and Input Bounds

λ	Nitrogen (lbs./acre)	Water (acre-inch)	Expected Net Returns ($)	Standard Deviation of Returns ($)
.0	500.0	76.8	678	338
.008	441.7	76.8	659	331
.010	305.4	55.1	530	284
.012	223.1	40.2	423	248
.014	147.0	37.2	356	225
.020	100.0	37.2	309	211

The constraint, $l_i \leq x_i \leq u_i$, forces inputs to be within specified lower and upper ranges.

Optimal Input Usage under Uncertainty

It is well known that risk considerations may distort input usage and output levels from competitive solutions obtained under parameter certainty (Robison and Barry). Interior solutions to (6) will be characterized by the following necessary condition:

$$(7) \qquad \frac{\partial CE}{\partial x_i} = \bar{p}\frac{\partial f}{\partial x_i} - r_i - \frac{\lambda}{2} a_i = 0,$$

where

$$a_i = (\bar{p}^2 + \sigma^2)\frac{\partial h}{\partial x_i} + 2\sigma^2 \frac{\partial f}{\partial x_i} f(x_N, x_W).$$

Use of x_i may differ from under certainty and risk neutrality (Pope). Input use will increase until the marginal value product (MVP) of the input equals input cost, r_i, plus the risk term measured by the interaction of various moments of the price and yield distributions, weighted by decision-maker attitudes towards risk.

In addition, rates of technical substitution between inputs also will be affected by their differential marginal contributions to yield variance. Equating the input price ratio with risk-adjusted marginal value products yields:

$$(8) \qquad \frac{r_N}{r_W} = \frac{\bar{p}\, \partial f/\partial x_N - \lambda/2 a_N}{\bar{p}\, \partial f/\partial x_W - \lambda/2 a_W}.$$

Factor levels and proportions thus will be affected by input and output prices, output price variance, output level, marginal products, risk aversion, and the marginal contributions of x_N and x_W to output variance. Changes in policy variables necessary to change factor levels will likely differ between the uncertain case depicted in (7) and the tangency conditions resulting under certainty.

If society deems the current use of x_N nonoptimal, two possible ways to effect changes in nitrogen use are: (*a*) alter the relative prices of x_N and x_W; or (*b*) place constraints on allowable levels of x_N.

Application to A Single Crop

Data from the Yuma Mesa, Arizona, station reported in Hexem and Heady were used to estimate a Just-Pope type production function for cotton seed and lint production.

Coefficients for the three-stage estimation procedure are reported in table 1. Average costs for water and fertilizer application and other average costs of production were calculated from University of Arizona enterprise budgets. Water cost was $1.10 per acre-inch and total fertilizer cost (including application) was $.13 per pound. Other variable costs of production totaled $405.33 per acre. Mean and variance of output price were calculated from 11 years (1976–86) of annual Arizona prices for cotton and lint [U.S. Department of Agriculture (USDA)]. Prices were deflated to 1987 dollars using the Consumer Price Index.

Optimal input levels under differing levels of risk aversion were determined by solving problem (6) for different values of λ. Upper and lower bounds were placed on the water and nitrogen activities corresponding to the ranges tested in the original field studies. Results are reported in table 2. Both water and nitrogen use were at their upper limits under risk neutrality (λ = 0). For increasing λ, reductions were first observed in nitrogen. For continued increases in λ, water inputs were reduced. Since both water and nitrogen reduce yield variability, these results appear contradictory. However, yield variance is but one term in the variance of profit expression (4). Effects of input reductions on expected yields, and consequently profit variance, outweighed the yield variance increases with reduced input use. Interior solutions were found for values of λ between about .008 and .013.

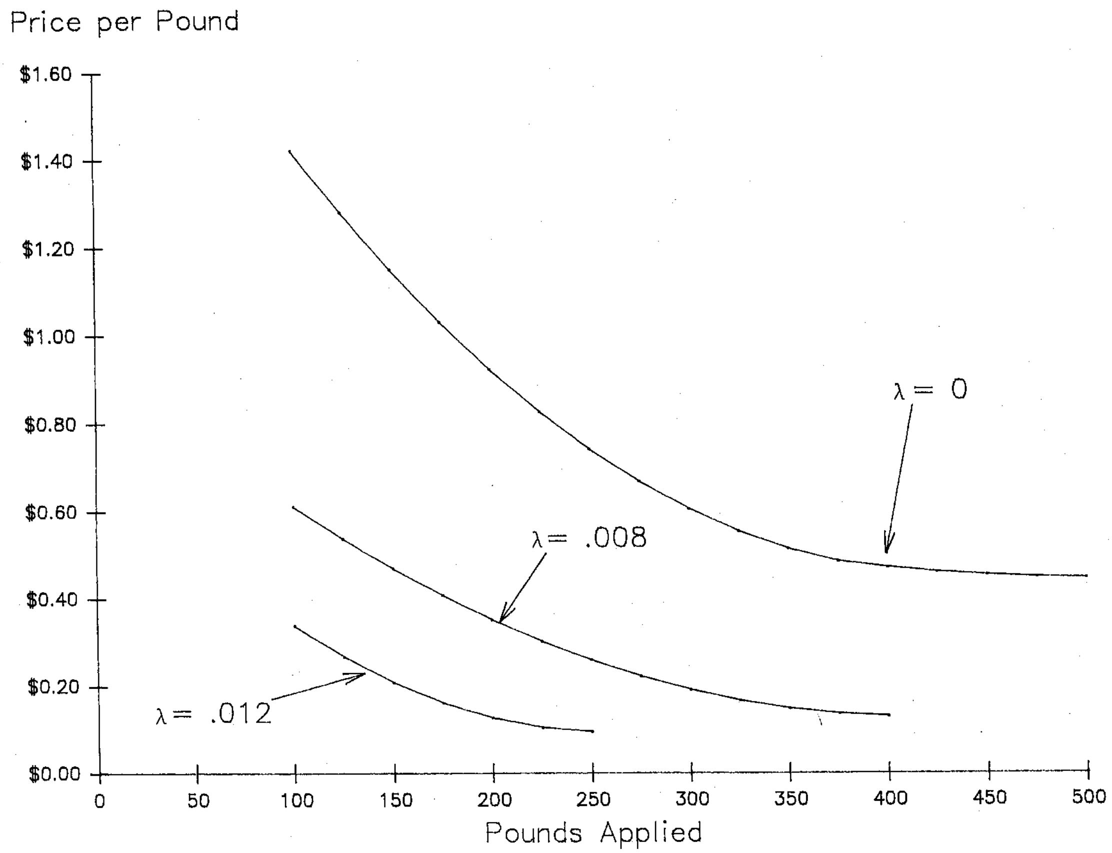

Figure 1. Fertilizer demand curves for λ = 0, .008, and .012

Farm Impacts of Reduced Nitrogen Input Levels

Tax Impacts

A per-unit tax on fertilizer may reduce fertilizer use by altering relative prices of different inputs. However, as seen in (8), tax levels necessary to achieve predetermined input levels will be sensitive to risk attitudes of the producer, as well as to the marginal impacts of the input on both expected returns and the variance of returns.

In order to determine impacts of different tax levels on fertilizer demand, application costs were ranged upwards from the initial $.13 per pound. Problem (6) was solved under risk neutrality ($\lambda = 0$) and two levels of risk aversion ($\lambda = .008$ and $\lambda = .012$).

Responses to the changing nitrogen cost were sensitive to values of the risk aversion parameter. Inverse demand functions for the three λ values used are reported in figure 1.

The difficulty faced by the policy maker empowered to establish the appropriate tax rate for achieving a desired level of fertilizer use is apparent. Behavioral responses will depend, in part, on the individual producer's attitudes towards risk.

Optimal input use and substitutability between inputs have different marginal risk effects as determined by (7) and (8). The resulting demand curve under risk neutrality shows that input use does not fall from the 500-pound upper bound until total input cost exceeds about $.40.

Small changes in fertilizer cost will, however, change optimal input levels over certain ranges of the risk aversion value. For example, when fertilizer cost is equal to $.13 per pound, the risk-adjusted cost ($\lambda = .012$) intercepts the MVP curve at the initial solution (fertilizer = 224 pounds). Reductions in fertilizer use due to a tax increase result from changes in both the marginal impact of fertilizer on expected returns and the variance of returns. Changes

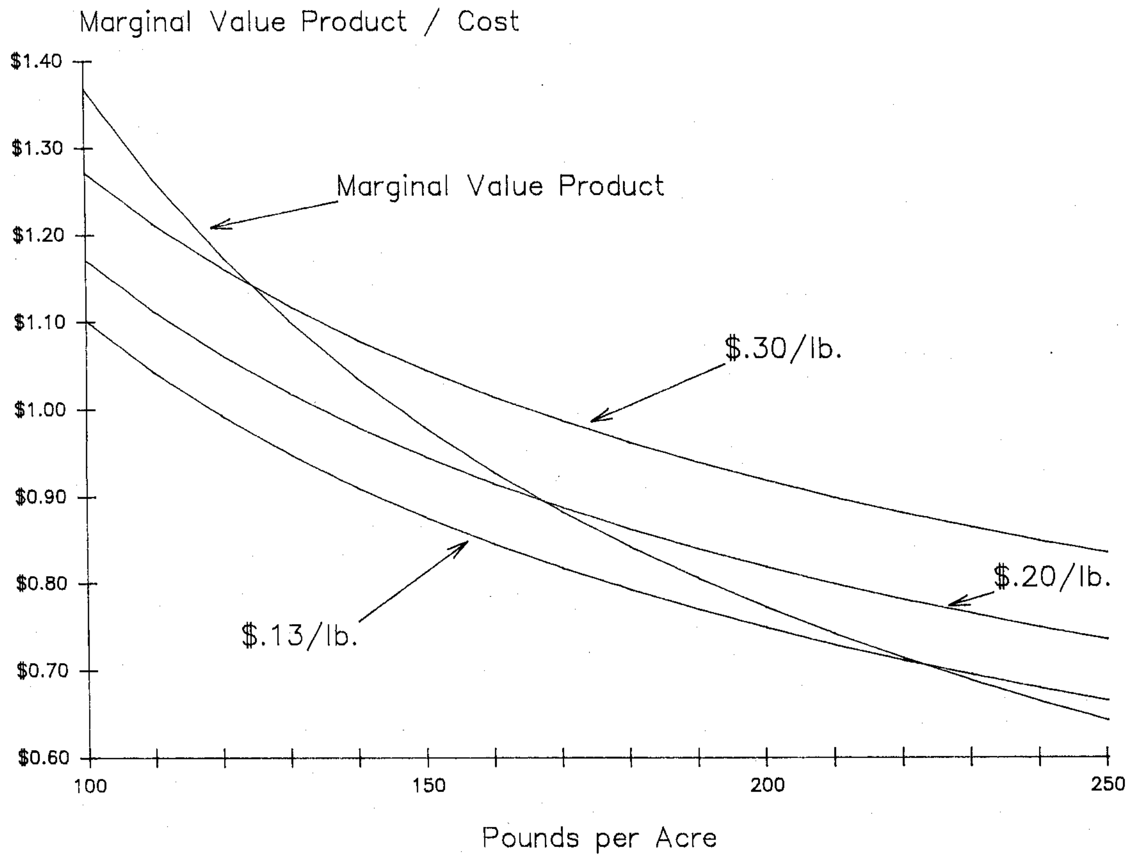

Figure 2. Marginal value product and selected risk-adjusted fertilizer costs for λ = .012

in the risk-adjusted fertilizer cost are seen in figure 2 for selected levels of the per-unit tax for λ = .012.

Impacts of Input Constraints

Farm impacts of quantity restrictions were assessed by placing increasingly restrictive upper bounds on fertilizer. Results are reported in table 3 for three different levels of risk aversion. As pointed out by Jacobs and Casler, the marginal cost reported on the fertilizer constraint represents the amount of tax that would be required to achieve the quantity restriction.

Comparison of Tax and Quantity Restrictions

The results obtained are consistent with Buchanan and Tullock's conclusion that the individual polluter will generally prefer a quantity restriction to taxes under equal levels of control. Figure 3 illustrates the situation for the risk-averse decision maker when the risk-adjusted cost of the input is downward sloping.[1]

Consider N_0 as the optimal level of input use without taxes or quantity restrictions and N_1 the use level deemed appropriate by the regulatory agency. The additional cost to the polluting firm of the tax over the quantity restriction will be area *t a b f*, or the per-unit tax times input use.[2]

Estimates of the additional costs of ignoring producer risk attitudes in developing control policies can be determined from table 4. Im-

[1] Identical results obtain under assumptions of risk neutrality or upward-sloping, risk-adjusted input cost. The situation in figure 3 was chosen because of its reflection of the effects of the policies on a risk-averse cotton producer.

[2] If one is willing to make additional assumptions about the return of the tax income to the firm in direct subsidy or reductions in other taxes, or if the expense of the tax can be passed on to consumers, the firm may be indifferent between the tax and the use restriction. However, Buchanan and Tullock's results apply when the firm is forced to absorb the full cost of the tax.

position of a per-unit tax of $1.03 per pound of fertilizer in order to induce the risk-neutral producer to reduce input use to 150 pounds per acre greatly overstates the tax rate required to induce risk-averse producers to reduce use to the same level. Conversely, a tax of $.09 per pound would have no effect on the risk-neutral producer (within the bounds of input use used here), yet would cause the farmer with a risk-aversion value of .012 to limit his/her input use to the 150-pound goal.

Alternative Enterprise Selection

One limitation facing the decision maker modeled in the previous section was the inability to switch to alternative crop enterprises under changing relative costs and/or fertilizer restrictions. When faced with new rules concerning the use of nitrogen fertilizer, the farmer might switch to different enterprises to mitigate the impact of the policy.

Three additional crops were added to the model. Data reported in Hexem and Heady again served for calculating Just-Pope type yield response functions for corn, sugar beets, and wheat. Coefficients of the three-stage estimation procedure are reported in table 5. Means and the variance-covariance matrix of prices were calculated from Arizona prices for cotton, wheat, and corn (USDA). Arizona prices for sugar beets were not reported, so U.S. average prices were used for this crop. Annual deflated prices for the years 1976–86 were used.

The nonlinear programming model in (6) was expanded to include additional crops. Expected net returns will be the summation of the returns accruing to each crop in the enterprise mix:

$$E(\pi) = \sum_{i=1}^{4} LAND_i \cdot [p_i f^i(x_{Ni}, x_{Wi}) - r_N x_{Ni} - r_W x_{Wi} - VC_i], \tag{9}$$

where $LAND_i$ is acreage devoted to crop i, subscript i refers to the ith crop, and the other variables are as defined earlier.

The variance of net returns will be:[3]

$$\mathrm{Var}(\pi) = \sum_{i=1}^{4} LAND_i^2 \sigma_i^2 + 2 \sum_{i>j}^{4} \sum^{3} LAND_i LAND_j \cdot \mathrm{Cov}(\pi_i, \pi_j). \tag{10}$$

The full model for maximizing the certainty equivalent with alternative crops will be:

$$\max CE = E(\pi) - \lambda/2 \mathrm{Var}(\pi) \tag{11}$$

subject to

$$l_{ki} \leq x_{ki} \leq u_{ki} \; for \; k = N, W$$
$$i = 1, 4$$

and

$$\sum_{i=1}^{4} LAND_i \leq TLAND,$$

where *TLAND* is the total land available.

Characteristics of the optimal solutions with initial fertilizer application costs and no use constraints are given in table 6.

Reductions in nitrogen use next were insti-

Table 3. Single Crop Impacts of Fertilizer Restrictions

Fertilizer Use (lbs.)	Per-Acre Marginal Cost of Restriction	Expected Profit	Standard Deviation of Profit
λ = 0		($)	
500	0.30	678	338
400	0.39	644	325
300	0.53	599	309
200	0.79	535	288
150	1.03	490	274
100	1.49	428	255
λ = .008			
442	0.00	659	331
400	0.02	644	325
300	0.08	599	309
200	0.21	535	288
150	0.33	490	274
100	0.58	428	255
λ = .012			
223	0.00	423	248
200	0.02	416	245
150	0.09	393	238
100	0.23	357	228

[3] An approximation for $\mathrm{Cov}(\pi_i, \pi_j)$ is derived in Bohrnstedt and Goldberger.

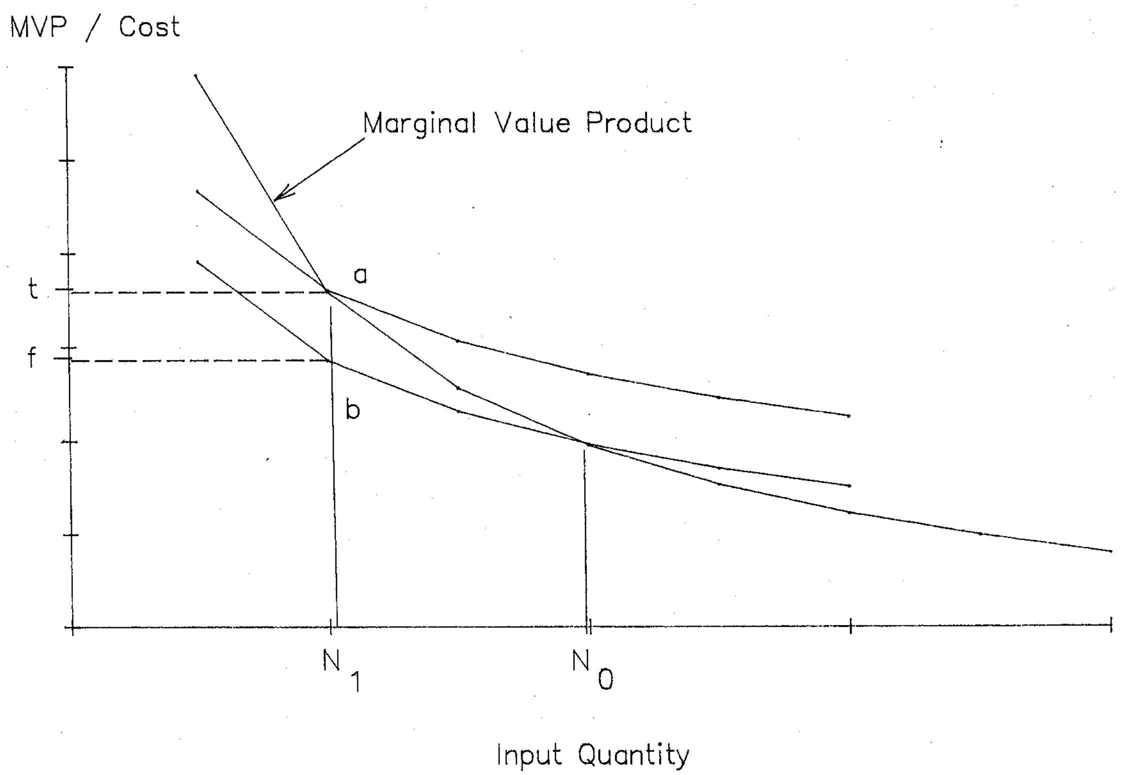

Figure 3. Tax versus quantity impacts of constraining nitrogen use to N_1 (f is risk-adjusted fertilizer cost and t-f is the per-unit tax)

tuted by imposing a per-unit tax on fertilizer and by imposing increasingly stringent use restrictions on permitted applications. Whereas the impact on the certainty equivalent of net returns is negative, as it was under the single-crop case, the effects are somewhat mitigated by the ability to diversify into other enterprises.

Table 4. Single Crop—Comparisons of Net Cash Incomes, Standard Deviations of Returns, and Certainty Equivalents of Per-Unit Tax and Fertilizer Restrictions Designed to Achieve Fertilizer Input Levels of 150 Pounds per Acre

	$\lambda = 0$	$\lambda = .008$	$\lambda = .012$
	($)		
Per-Unit Tax	1.03/lb.	0.33/lb.	0.09/lb.
Expected Return	335	437	379
Standard Deviation	274	273	238
Certainty Equivalent	335	138	39
Quantity Restriction			
Expected Return	490	490	393
Standard Deviation	274	274	238
Certainty Equivalent	490	189	53

A sample of the output results are reported in table 7. Conclusions regarding the relative farm impacts of a per-unit tax on fertilizer use and of quantity restrictions are similar to those found under the single-crop example. As shown in the last section, the greater impact of the tax results from the difference in the per-unit cost of fertilizer, $r_N^t - r_N^r$, times the amount of fertilizer used. The sensitivity of the policy responses to risk attitudes also can be seen in table 7. Similar to the single-crop example, tax rates adequate to attain compliance by the more risk-averse farmers will have little effect on the risk-neutral producer.

Multiple Farms with Diverse Risk Attitudes

The previous section compared the impacts of tax incentives and use restrictions for a single farm. The final section represents an applica-

Table 5. Coefficients from the Three-Stage Estimation of the Just-Pope Production Function for Sugar Beets, Wheat, and Corn: $y = Ax_W^{\alpha_W} x_N^{\alpha_N} + Bx_W^{b_W} x_N^{b_N} + \epsilon$

A	α_W	α_N	B	b_W	b_N
Sugar Beets					
87.550	0.576	0.621	3.277	1.451	−0.140
(77.105)	(.180)	(.081)	(3.077)	(.658)	(.247)
Wheat					
32.693	1.375	0.063	5.695	−0.069	0.079
(12.390)	(.122)	(.005)	(3.226)	(.607)	(.032)
Corn					
704.590	0.446	0.040	9.379	−0.226	−0.496
(1.000)	(.040)	(.026)	(2.551)	(.545)	(.244)

Note: Standard errors are in parentheses.

tion of the developed approach to a multifarm context.[4] The model was reformulated such that the sum of certainty equivalents for three farms characterized by risk aversion parameters of $\lambda = 0$ (farm 1), .008 (farm 2), and .012 (farm 3) is maximized. Comparisons are made between uniform taxes and standards versus applying different tax rates and standards against individual firms within the industry to meet nitrogen use goals.

The difference between uniform quantity restrictions and a uniform tax is illustrated in figure 4. The figure represents two firms facing different marginal costs associated with reducing nitrogen input levels. The traditional analysis of figure 4 assumes firms having different production technologies face different marginal costs of input or output control. An analogous situation occurs in the current case, where firms choose different throughput vectors because of alternative risk attitudes.

Suppose N_{0a} and N_{0b} are mandated restrictions on nitrogen use necessary to achieve a desired input rate of N_D. Alternatively, one can assume that regulators can determine an optimal tax rate, t, to obtain the same level of input use (i.e., $N_{1a} + N_{1b} = N_D$). From a social perspective, the tax generally is preferred because it allows firms to equate marginal cost of abatement to the tax, thus resulting in more efficient resource allocation. As Baumol and Oates state, "A tax rate set at a level that achieves the desired reduction in the total emission of pollutants will satisfy the necessary conditions for the minimization of the program's cost to society" (p. 168).

[4] Firms in the analysis are assumed to be price takers in both the input and the output markets.

Table 6. Production and Income Characteristics with Unrestricted Nitrogen Usage

	$\lambda = 0$	$\lambda = .008$	$\lambda = .012$
Crops Grown	Sugar Beets (1.0 acre)	Sugar Beets (1.0 acre)	Sugar Beets (0.79 acre) Cotton (0.11 acre) Corn (0.10 acre)
Nitrogen Use (lbs./acre)	565.0	565.0	503.8
		($)	
Expected Income	774	774	700
Standard Deviation	270	270	242
Certainty Equivalent	774	482	349

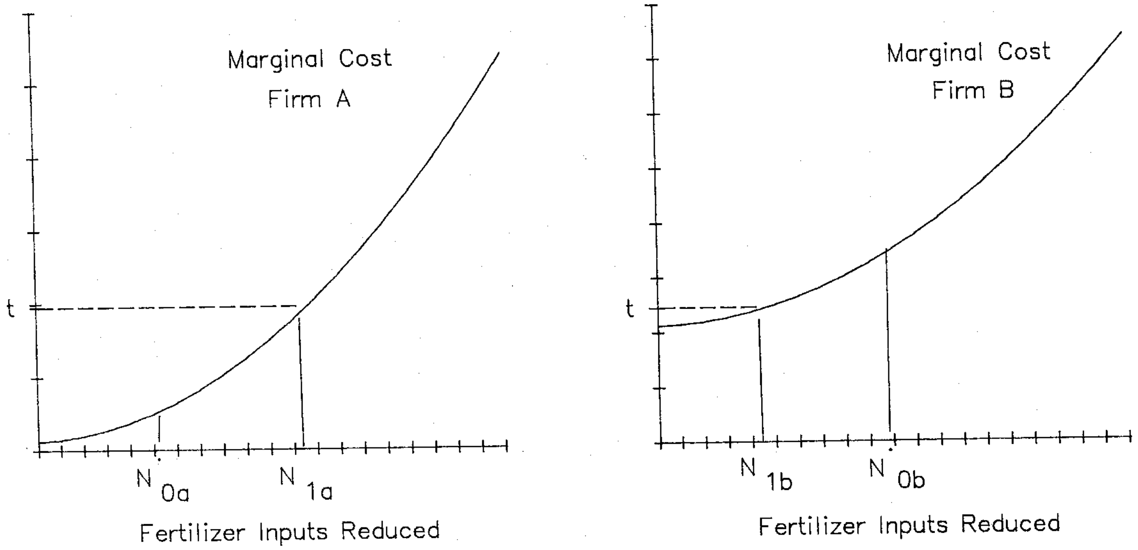

Figure 4. Uniform quantity restrictions versus uniform tax—two firms facing different marginal costs of reducing fertilizer use

However, the individual firms are still faced with the amount of the tax, $t{*}0N_{1a}$ or $t{*}0N_{1b}$, plus the integral of marginal cost from the origin to N_{1a} (or N_{1b}). Total cost to the firm necessarily will be greater under the tax.[5]

Results in tables 8a and 8b indicate private costs of attaining the regional goal would be lower if farmers were allowed to individually adjust use levels to achieve an average regional application rate of 150 pounds per acre. Certainty equivalents for farms 1 and 2 would be higher than when each farm was restricted to a rate of 150 pounds on each acre. Farm 3 would be the only loser, absorbing most of the use reduction necessary to achieve the regional goal. Income transfers from farms 1 and 2 to farm 3 should be possible to achieve the desired social goal and leave all producers at least as well off as they would be with a mandatory use rate of 150 pounds on each acre farmed. Private costs of compliance would be lower with the point-by-point quantity restrictions than they would be with a uniform restriction applied to each of the three farms.

Impacts of taxes levied to achieve both the uniform and the aggregate input goals also are reported in tables 8a and 8b. Each producer would again prefer the quantity restriction to the tax for equal levels of control. Distributional impacts of the uniform versus the differential tax are similar to those achieved under the quantity restrictions. Two of the three farms are better off with the uniform tax in terms of the certainty equivalent of income. It is also interesting to note total tax collections by the collecting agency are higher with the uniform tax rate.[6] Allowing producers to ad-

[5] The only exception to this is if one assumes government revenues remain unchanged with the tax, thus resulting in corresponding reductions in other taxes affecting the firms or, at the extreme, a return of the collected taxes to the firms themselves.

[6] Taxes collected under the uniform tax rate are \$.73 (215.8 + 203.7 + 30.7) or \$328.60. Total tax with the uniform 150-pound use per acre is 150 (\$1.03 + \$.38 + \$.13) or \$231.

Table 7. Multiple Crops—Comparisons of Net Cash Incomes, Standard Deviations of Returns, and Certainty Equivalents of Per-Unit Tax and Fertilizer Restrictions Designed to Achieve Fertilizer Input Levels of 150 Pounds per Acre

	λ = 0	λ = .008	λ = .012
		($)	
Per Unit Tax	1.03/lb.	0.38/lb.	0.13/lb.
Expected Return	335	305	303
Standard Deviation	274	183	142
Certainty Equivalent	335	171	182
		($)	
Quantity Restriction			
Expected Return	490	363	322
Standard Deviation	274	183	142
Certainty Equivalent	490	229	201

Table 8a. Multiple Crops—Per Farm Reductions—Income and Certainty Equivalent Impacts of Use Restrictions (Restrict) and Input Taxes (Tax)

Attain 150-Pound Use Rate on Each Acre for Three Farms

	λ = 0		λ = .008		λ = .012	
Crops Grown	Cotton (1.0 acre)		Cotton (0.53 acre) Corn (0.47 acre)		Wheat (0.77 acre) Cotton (0.23 acre)	
Nitrogen Use (lbs./acre)	150		150		150	
Shadow Price on Nitrogen Constraint	$1.03		$0.38		$0.13	
	Restrict	Tax	Restrict	Tax	Restrict	Tax
	($)					
Expected Income	490	335	363	305	322	303
Standard Deviation	274	274	183	183	142	142
Certainty Equivalent	490	335	229	171	201	182

Table 8b. Multiple Crops—Reducing Average Use over Three Farms—Income and Certainty Equivalent Impacts of Use Restrictions (Restrict) and Input Taxes (Tax)

Attain 150-Pound Average Use Rate on Each Acre for Three Farms

	λ = 0		λ = .008		λ = .012	
Crops Grown	Cotton (1.0 acre)		Wheat (0.66 acre) Sugar Beets (0.34 acre)		Wheat (0.90 acre) Cotton (0.10 acre)	
Nitrogen Use (lbs./acre)	215.8		203.7		30.7	
Shadow Price on Nitrogen Constraint	$0.73		$0.73		$0.73	
	Restrict	Tax	Restrict	Tax	Restrict	Tax
	($)					
Expected Income	546	389	393	243	225	203
Standard Deviation	292	292	123	123	101	101
Certainty Equivalent	546	389	333	183	164	142

just to the tax of $.73 per pound to achieve the average use goal results in less private cost, on aggregate, than the differential taxes required for the uniform use level.

Summary and Conclusions

Previous empirical work analyzing alternative agricultural input control institutions often has ignored the influence of uncertainty and decision-maker risk aversion on individual farm costs (Stevens). It is well known that optimal input levels may be different for the risk-averse firm under uncertainty than optimal levels predicted under certainty and risk neutrality. Analyses of farm impacts of pollution control policies may thus over- or underestimate costs, depending upon the direction of the marginal contribution of the offending input to riskiness of returns.

Use of the Just-Pope type production function allows costs of alternative control measures to be estimated in terms of both expected returns and the variance of returns. Costs of controls differed significantly between the profit-maximizing and the risk-averse decision makers for both the single-crop and the multiple-crop examples. Policy makers who do not account for the effects of uncertainty and differential risk attitudes may not even attain the second-best control institution mentioned by Russell.

An additional comment concerns the choice of technologies available to the firm. Although direct incorporation of the production function is an improvement over earlier, linearly constrained models designed to estimate farm costs of emission controls, no technologies were available within the model to incorporate inputs that might substitute for nitrogen-based inorganic fertilizers. As Saliba mentioned, the form of the nitrogen in the fertilizer is important in estimating potential runoff damages. Alternative production technologies may be available having less impact on the distribution of yields than the single technology modeled here. If and when the production characteristics of these alternative technologies are determined, they could be incorporated into the present model to determine incentive systems for promoting their adoption by producers of varying risk attitudes.

A final comment relates to the partial analysis reported here. A comprehensive analysis of policies designed to estimate the impacts of achieving environmental goals must include the variety of production technologies available to all firms within a targeted industry, as well as model general equilibrium impacts if policies have significant consequences on input and output markets. Environmental benefits of controls also should be included to equate marginal social costs with benefits of the policy in question. It is hoped that the model developed and reported in this article will enable subsequent studies of the impacts of agricultural pollution control alternatives to incorporate risk considerations in the estimate of private costs.

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References

Ayer, H., P. Hoyt, B. Gardner, B. Roth, and T. Doerge. "Cutting Nitrogen Applications for Improved Water Quality: Does the Farmer Lose?" Papers of the 1989 Annual Meeting, West. Agr. Econ. Assoc., July 1989: 533–40.

Batie, S. S. "Agriculture as the Problem: New Agendas and New Opportunities." *S. J. Agr. Econ.* 20 (July 1988):1–11.

Baumol, W. J., and W. E. Oates. *The Theory of Environmental Policy,* 2nd ed. Cambridge: Cambridge University Press, 1988.

Bohrnstedt, G. W., and A. S. Goldberger. "On the Exact Covariance of Products of Random Variables." *Amer. Statist. Assoc. J.* 64(1969):1439–42.

Buchanan, J. M., and G. Tullock. "Polluters' Profits and Political Response: Direct Controls Versus Taxes." *Amer. Econ. Rev.* 65 (March 1975):139–47.

Hexem, R. W., and E. O. Heady. *Water Production Function for Irrigated Agriculture.* Ames: Iowa State University Press, 1978.

Jacobs, J. J., and G. L. Casler. "Internalizing Externalities of Phosphorus Discharges from Crop Production to Surface Water: Effluent Taxes versus Uniform Reductions." *Amer. J. Agr. Econ.* 61(1979):309–12.

Just, R. E., and R. D. Pope. "Stochastic Specifications of Production Functions and Econometric Implications." *J. Econometrics* 7(1978):67–86.

Mood, A. M., F. A. Graybill, and D. C. Boes. *Introduction to the Theory of Statistics,* 3rd ed. New York: McGraw-Hill Book Co., 1974.

Nielsen, E. G., and L. K. Lee. "The Magnitude and Costs of Groundwater Contamination from Agricultural Chemicals: A National Perspective." U.S. Department of Agriculture Econ. Res. Serv., AER 576, October 1987.

Pope, R. D. "Expected Profit, Price Change, and Risk Aversion." *Amer. J. Agr. Econ.* 64(1982):581–84.

Robison, L. J., and P. J. Barry. *The Competitive Firm's Response to Risk.* New York: Macmillan, 1987.

Russell, C. S. "A Note on the Efficiency Ranking of Two Second-Best Policy Instruments for Pollution Control." *J. Environ. Econ. and Manage.* 13(1986):13–17.

Saliba, B. C. "Irrigated Agriculture and Groundwater Quality—A Framework for Policy Development." *Amer. J. Agr. Econ.* 67(1985):1231–37.

Shortle, J. S., and J. W. Dunn. "The Relative Efficiency of Agricultural Source Water Pollution Control Policies." *Amer. J. Agr. Econ.* 68(1986):668–77.

St. Onge, J. "Runoff Runs Amok." *Sierra.* Vol. 73, No. 6. (November/December 1988):28–32.

Stevens, B. K. "Fiscal Implications of Effluent Charges and Input Taxes." *J. Environ. Econ. and Manage.* 15(1988):285–96.

U.S. Department of Agriculture. *Agricultural Statistics,* various issues.